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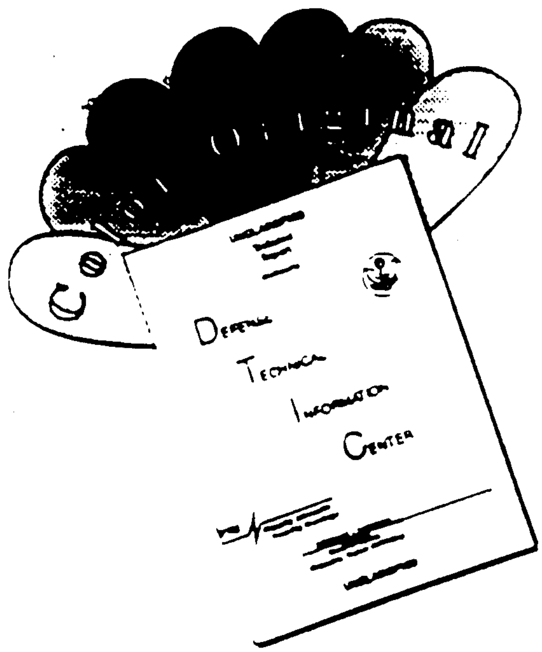

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TECHNICAL NOTE 96-2

DEMONSTRATION OF A REAL TIME CAPABILITY TO PRODUCE TIDAL HEIGHTS AND CURRENTS FOR NAVAL OPERATIONAL USE: A CASE STUDY FOR THE WEST COAST OF AFRICA (LIBERIA)

by

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24 May 1996

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EXECUTIVE SUMMARY

This report documents an existing capability to produce operationally relevant products on sea level and currents from a tides/storm surge model for any coastal region around the world within 48 hours from the time of the request. The model is ready for transition to the Naval Oceanographic Office (NAVOCEANO) for potential contingency use anywhere around the world. A recent application to naval operations offshore Liberia illustrates this.

In April 1996, political turmoil in Liberia prompted an emergency evacuation of U.S. Citizens from Monrovia, prompting NAVOCEANO to anticipate a possible U.S. Navy operation along the south-western coast of Africa. The ADCIRC model (Luettich et al., 1992; Westerink et al., 1994) providing the present tidal prediction capability at NAVOCEANO, could not be readily extended to the region. So, NAVOCEANO contacted CAST and CU to see if they could use their relocatable R&D model for support. Working together, MSU CAST, CU and NAVOCEANO successfully deployed the CURReNTSS (Colorado University Rapidly Relocatable Nestable Tides and Storm Surge) model that predicts sea surface height, tidal currents and storm surge, and provided operational products on tidal sea level and currents in the littoral region off south-western coast of Africa. This report summarizes the results of this collaborative effort between CAST, CU and NAVOCEANO in an actual contingency use of the relocatable model, summarizes the lessons learned, and provides recommendations for further evaluation and transition of this modeling capability to operational use.

The quality of operational products depends to a large extent on the availability of accurate, fine-resolution data bases such as bathymetry/hydrography data sets and wind forcing (NORAPS/COAMPS). It is recommended that NAVOCEANO establish these data bases in advance, **preferably on a global basis**, and if that is problematic, at least for high-risk regions so that potential operational numerical models can be relocated successfully, rapidly and efficiently. For emergency situations where a high resolution data base is not already available, an appropriately trained tiger team should be established to derive the required data sets for any region in a short time frame.

The Liberian application has provided useful information on the rapid relocatability, real time operation capability, and robustness of the model. It has demonstrated that with some refinements it can be transitioned to operational use. Research and operations personnel at NAVOCEANO Warfighting Support Center (WSC), Ocean Modeling Division (Code N531) and MSU CAST should determine the details. In addition, it is desirable that the CURReNTSS and the ADCIRC models be compared in a common environment where enough evaluation data are available, to ascertain the strengths and weaknesses of each so that the two models may be employed most advantageously in a complementary mode.

1. INTRODUCTION

The world's littoral zones, which include semi-enclosed, marginal and coastal oceans, have become increasingly important for naval operations. Littoral operational needs such as logistics demand a wealth of environmental information, that includes tides and storm surges. Because of the dearth of bottom pressure gage data in the coastal seas, both here and abroad, the only practical alternative for tidal sea surface height (SSH) is to use numerical models. High resolution models of coastal waters have the potential to provide this information, provided they can be nested in relatively and necessarily coarser tidal models of the world's of ocean basins.

In a joint collaborative effort under SPAWAR/ONR funding, Colorado University (CU) and Mississippi State University Center for Air Sea Technology (MSU CAST) have developed such a model, CURReNTSS (Colorado University Rapidly Relocatable Nestable Tides and Storm Surge). Because of a political crisis in Liberia, CAST was provided an opportunity to test the rapid model-relocation capability in a real contingency.

In April 1996, a political turmoil in Liberia prompted an emergency evacuation of U.S. Citizens from the capital city of Monrovia, prompting NAVOCEANO to anticipate a possible U.S. Navy operation along the south-western coast of Africa. The ADCIRC model, providing the present tidal prediction capability at NAVOCEANO, could not be readily extended to the region. NAVOCEANO was aware of the joint collaborative development effort of the CURReNTS model at CU/MSU CAST and contacted CAST to see if we would exercise CURReNTSS to support NAVOCEANO under this situation. Because of an earlier success in a feasibility study of the rapid model relocation in a coastal area near San Diego, California (see Appendix A), CAST agreed to provide this support.

This report summarizes the results of this collaborative effort between CAST, CU and NAVOCEANO in a real contingency relocation of the CURReNTS model, summarizes the lessons learned and provides recommendations for the further evaluation, enhancement and transition of this modeling capability to the operational Navy. The report is organized as follows. Section 2 provides a brief model description followed by the relocation methodology in Section 3. Section 4 deals in detail with the CURReNTSS model relocation effort to the Liberian coast. Since rapid relocation of the model is a major concern, we recreated the sequence and time line of events as they developed. This recreation brought into focus the major bottlenecks where the streamlining process needs to be emphasized. This is followed by the model prediction runs conducted on the coarse grid and the nested fine grid therein. To delineate the effect of the atmospheric forcings on the predictions of tidal heights and currents, the model is run with astronomical tidal forcing alone and then with both astronomical tides and surface wind forcing. In Section 5, some problems encountered in the CURReNTS implementation are highlighted and Section 6 provides some concluding remarks and recommendations. Also, since the San Diego implementation provided the necessary background and impetus to undertake this support task for the Liberian operation, its results are included as Appendix A.

2. BRIEF MODEL DESCRIPTION

CURReNTSS is a finite difference, explicit, vertically-integrated barotropic model capable of assimilating tidal component or sea level data from coastal tide gages and from any bottom pressure gages available. It is fully non-linear and a sub-component of the NAVOCEANO/CU 3-D operational model. The model incorporates direct astronomical tidal forcing (tide potential) and can also utilize surface forcing (winds stress, pressure fields) from atmospheric numerical weather prediction (NWP) models and analyses, to predict storm surges. The open boundary conditions for tides are obtained from a global tidal model run at 1/5° resolution (Kantha, 1995; Kantha et al., 1995), which is readily accessible from the graphical user interface (GUI).

The GUI defaults for bottom bathymetry to the ETOPO5 database, which can be edited within the GUI and setup for the model (Kantha et al., 1993; Pontius et al. 1994). It is also possible to import bathymetry from other databases into the GUI. The model can be run with any number of tidal components including long term and compound tides. It employs a simple data assimilation procedure by replacing the model predicted SSH at pre-determined intervals by a weighted sum of the model prediction and the observed SSH from the tide/bottom pressure at that grid point, the weights are determined a priori. The tide gage data come from the data base at the International Hydrographic Organization(1979), supplemented by the Admiralty charts (1993). This database is also available from the GUI and relevant tidal stations easily extracted and edited prior to assimilation by the model. Further details on the methodology and governing equations for the model can be found in Kantha et al.(1993); see also Pontius et al. (1994). Detailed results are also available as a multimedia Hypertext document at **http://www.cast.msstate.edu/Tides2D**.

3. METHODOLOGY

For applications to high resolution sea levels and currents along any coast, the procedure is to nest a high resolution local barotropic model at the desired resolution (1 – 5 km) and domain encompassing the coastal region of interest, within a larger domain at a rather coarse resolution (5 – 20 km). This is necessary for efficiency and practicality because the numerical modeling strategy used here relies on a finite-difference approach. It is an alternative approach to the finite-element based ADCIRC model that uses telescoping elements with increasing resolution as the coast is approached. However, CURReNTS model is expected to provide somewhat more robust results for barotropic (vertically-integrated) currents in the water column.

The model is multiply nestable. The approach works best when the data bases needed to initialize and force each nested component have appropriate resolution. A similar problem exists for the finite element approach as well – the resolution of data bases must be compatible with the highest grid resolution. The approach is to run the coarsest resolution CURReNTSS model with tidal boundary conditions derived from the CU high resolution global tidal model (that assimilates altimetric and tide gage data) and atmospheric pressure and wind stress derived from NWP products. The SSH output of this model is saved on the boundaries of the nested model at each time step for use in providing the boundary conditions to run the nested model. The nested modeling approach has been tested only for double-nesting, although it should work in principle to more than two levels of nesting.

4. AN OPERATIONAL CASE STUDY

For a model to be made operational, it is essential that the model be well-formulated, carefully calibrated and adequately validated. An initial feasibility study to check the viability of operational use of CURReNTSS model and to validate its results was performed earlier this year. The area chosen for this analysis was the west coast of the United States near San Diego, California, where high resolution winds and pressure fields were available from the DoD Master Environmental Library (see http://www-mel.nrlmry.navy.mil/). The model results were evaluated for both the "tides-only" mode as well as the "storm surge" mode, using wind forcing from COAMPS for January 1996. The details for the model setup and the results are presented in Appendix A.

A second opportunity to demonstrate the relocatability of CURReNTSS occurred in April 1996, when a political turmoil in the western African nation of Liberia prompted an evacuation effort by the Navy from Monrovia, the capital city of Liberia. A chronological listing of events for providing the Navy with real time tidal heights and currents for west coast of Africa is presented in the next section. This listing is followed by a description of the computational domain and setup parameters for the model. Finally, results from the model are analyzed and discussed.

4.1 Chronological Listing Of Events And Tasks Accomplished

04/12/96:

- NAVOCEANO (Code N531) indicated there was potential for an operational need for information on tidal heights and currents for the coast of Liberia. CAST agreed to attempt to provide this data using the relocatable CURReNTSS and the Tidal GUI.
- CAST's Tidal GUI provided the bathymetry using the 5′ DBDB5 data base, tidal station data (for assimilation) and boundary conditions for the selected coarse grid (see Section 4.2).

04/13/96:

- The model was initialized and CURReNTSS model completed a successful tidal run for the coarse grid. Significant support was provided by the University of Colorado.
- The output from the coarse grid run looked promising.
- The Tidal GUI was again used to setup the bathymetry and computational domain for the high resolution nested grid near Monrovia (see Section 4.2).

04/14/96:

- The high resolution tidal run was completed successfully and the output analyzed.
- The NOGAPS surface forcing fields were obtained and reformatted for storm surge analysis.

04/15/96:

- CAST provided the results for the tidal model runs to NAVOCEANO.
- The results were promising but CU, CAST and NAVOCEANO were concerned about the accuracy of the DBDB5 bathymetry and the resulting coastline used for the nested high resolution model run. There was an offset of 10 km in the shoreline when compared to the World Vector Shoreline. The DBDB5 bottom depths can also be in excess of 100% error in shallow water.
- NAVOCEANO agreed to provide accurate high resolution bathymetry (from shoreline to 200 m depth) using maritime charts.
- CAST further refined the coastline in the bathymetry using the World Vector Shoreline database from the Tidal GUI.

04/16/96:

- NAVOCEANO and CAST put together a higher resolution digitized bathymetry for the area of interest based on contoured maritime charts.
- The high resolution nested model was rerun using the refined coastline and improved bathymetry.

04/17/96:

- The output for the new run was post-processed and analyzed. The results were delivered to the Weather Watch workstation within the WSC at NAVOCEANO. The WSC requested reformatting of the model output (change of units, time series etc.) to enhance the operational relevance and ease of use of the results.
- CAST provided NAVOCEANO with reformatted model results. (see Section 4.3)

4.2 Model domains and set-up

At the very outset, the regional extent and resolution of the nested models were decided upon in close consultation with NAVOCEANO and CU.

4.2.1 Coarse Grid

The physical domain for the coarse grid stretches from the equator to 15 ° N, and 5° to 20° W (see Figures 1a and 1b). The area of interest included the cities of Monrovia (Liberia), Freetown (Sierra Leone) and the entire Liberian coast. At a resolution of 1/5 °, the model was run on a 76 $\times$ 76 grid on an SGI workstation. As shown in Fig. 1a, the domain had open boundaries on all four sides. These boundary conditions were provided using the database of global results (at 1/5° resolution) available via the GUI. In all, 35 tidal stations were found in this domain, but only 22 were retained. The others were excluded based on their location (protected harbors, etc). The same weight (the gage was weighted 90 %, the model 10 %) was given to all tide gages for assimilation in the model. The bathymetry was also setup using the GUI and the DBDB5 database (see Figure 1b).

The barotropic (external) time step was chosen as 30 seconds and the bottom drag coefficient as 0.0025. First, the coarse grid model was run for 15 to 26 April with a prior spin up of one day. Boundary conditions for the fine grid model were saved every time step. These were then interpolated to the fine grid resolution and the fine grid model was then run to provide the results needed at four locations mentioned below. Because of their strategic importance, two locations (Freetown and Monrovia) were selected to save time series output for tidal heights and currents.

West Coast of Africa

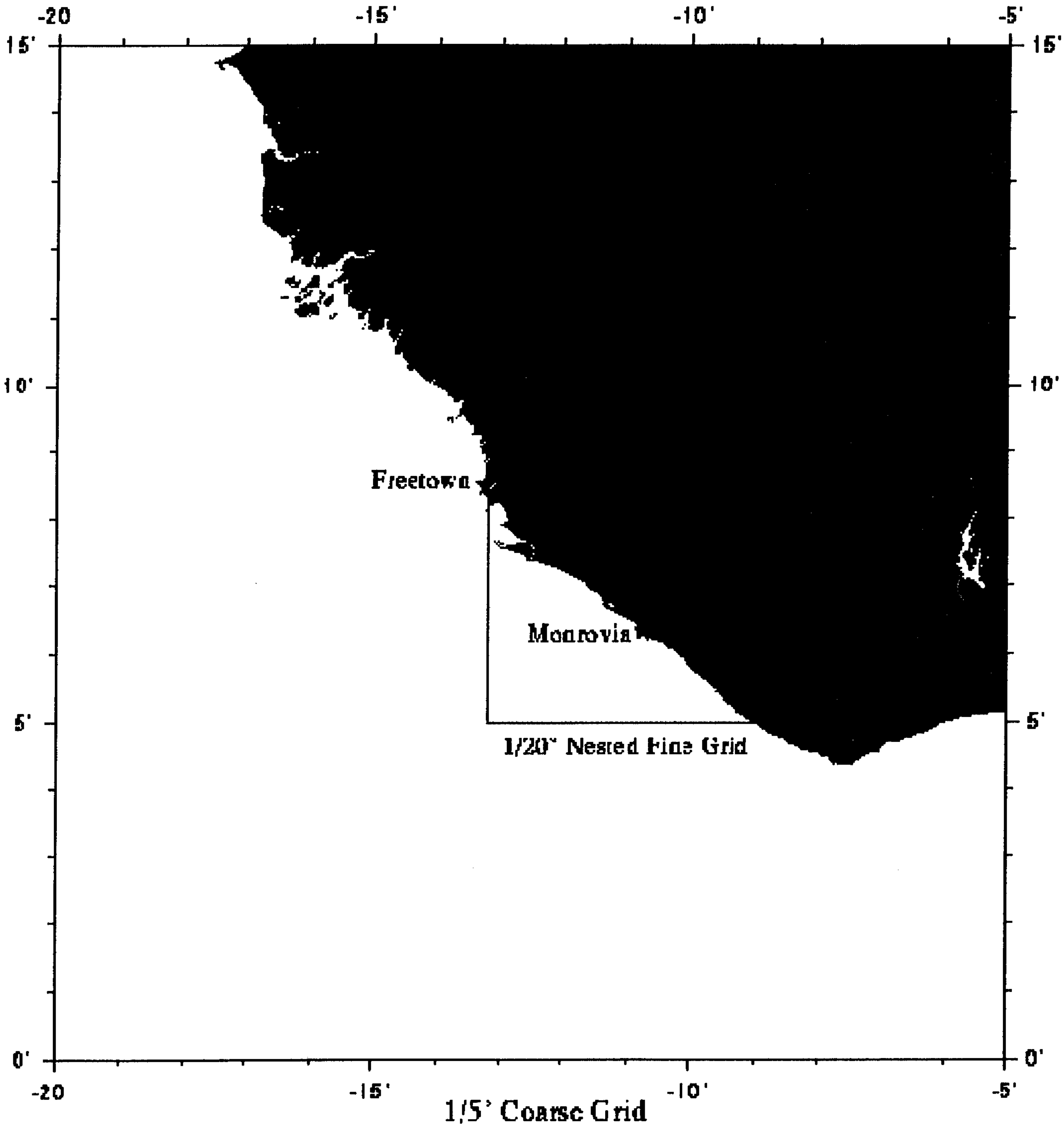


Figure 1(a). Physical Domains for the Coarse and Fine (nested) Grids.

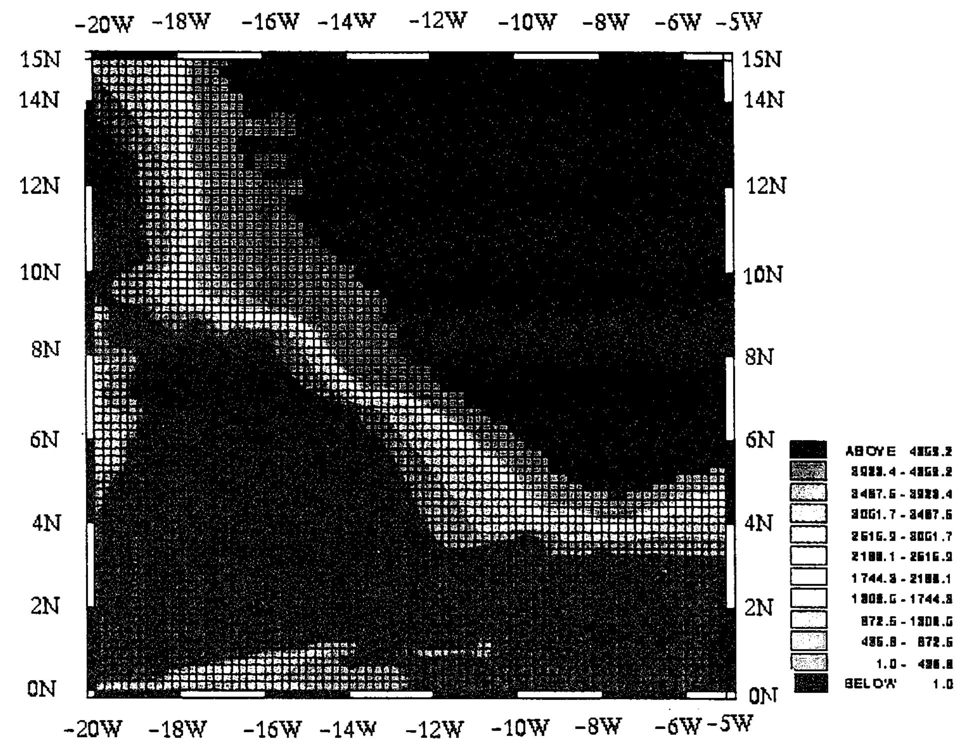


Figure 1 (b). Coarse Grid and Bathymetry (in meters)

4.2.2 Fine Nested Grid

The high resolution nested grid extended from 5° to 8.4° N, and 8.7° to 13.2° W (see Figures 1a and 1c). At 1/20°, the grid resolution was four times finer than the coarse grid. The selected domain yielded a 89×69 grid with two open boundaries (West and South). The boundary conditions were provided from the output of the coarse model run saved at the open boundaries of the nested domain. Data from the only two tidal gages available were assimilated.

The barotropic time step was reduced to 8 seconds. The bottom drag coefficient was kept the same. A refined coastline and an accurate high resolution bathymetry was used (see Figure 1c). Time series output for tidal heights and currents was saved at four locations evenly located along the coast: Sheather Rock in Sierra Leone and Kasi, Monrovia and Little Kola in Liberia.

4.3 Results (Tides Only)

4.3.1 Coarse Grid

The coarse grid model was run for 11 days from rest with the starting date of April 15, 1996. The first day was used for ramp-up and results predicted for the next 10 days through April 25, 1996. Only forcing from astronomical tides was applied and seven tidal constituents: M_2, S_2, N_2, K_2, K_1, P_1 and Q_1 were included (assimilation data for O_1 component was unavailable and so O_1 was excluded).

The time series output for tidal SSH and currents at the two location chosen a priori, Freetown (8.5° N, 13.23° W) and Monrovia (6.33° N, 10.8° W), are shown in Figs. 2 and 3 respectively. The tidal elevation above mean water level (measured in feet) is shown in blue and the magnitude of the barotropic tidal currents (measured in knots) is shown in red. From the plots, it can be seen that the semi-diurnal tidal constituents dominate the tides. The maximum tidal heights are 3.6 ft. at Freetown and 2.25 ft. at Monrovia both occurring on April 16th. As expected, the maximum tidal currents also occur at the same time and range up to about 0.156 kts (at Freetown). In comparison, the currents were found to be significantly smaller at Monrovia.

To generate streak plot movies, output was also saved at every half hour interval. A few snapshots of these streak plots are shown in Figs. 4 and 5. The maximum tidal currents are found North of Freetown along the Sierra Leone coast which can be attributed to the presence of a broad continental shelf at the northern boundary of the domain.

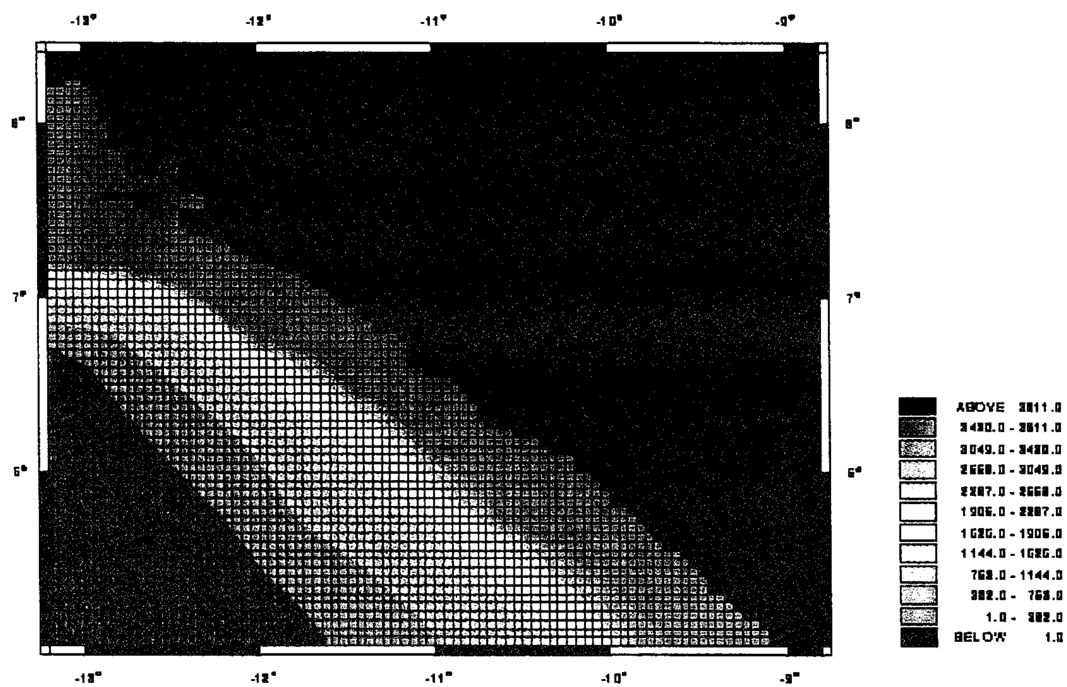


Figure 1 (c). Fine Grid and Bathymetry (in meters)

Prototype Tidal Model Elevation & Depth–Averaged Currents:

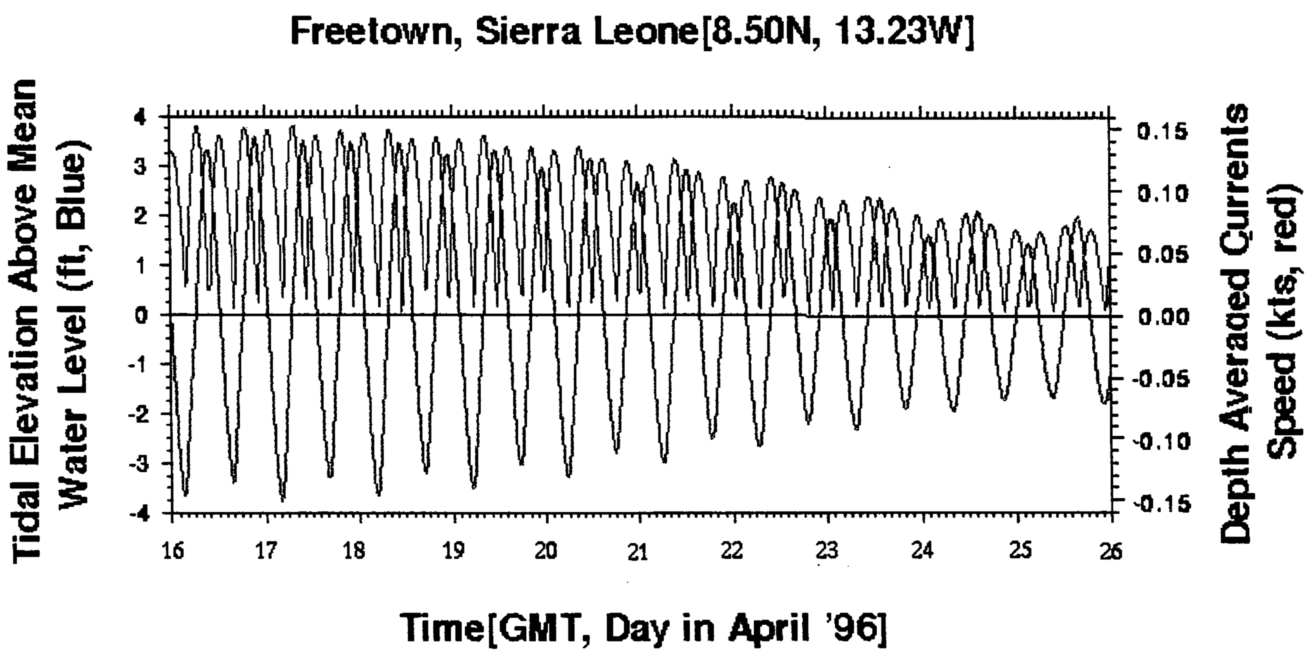


Figure 2. Time Series plots for Freetown (Coarse Grid)

Prototype Tidal Model Elevation & Depth–Averaged Currents:

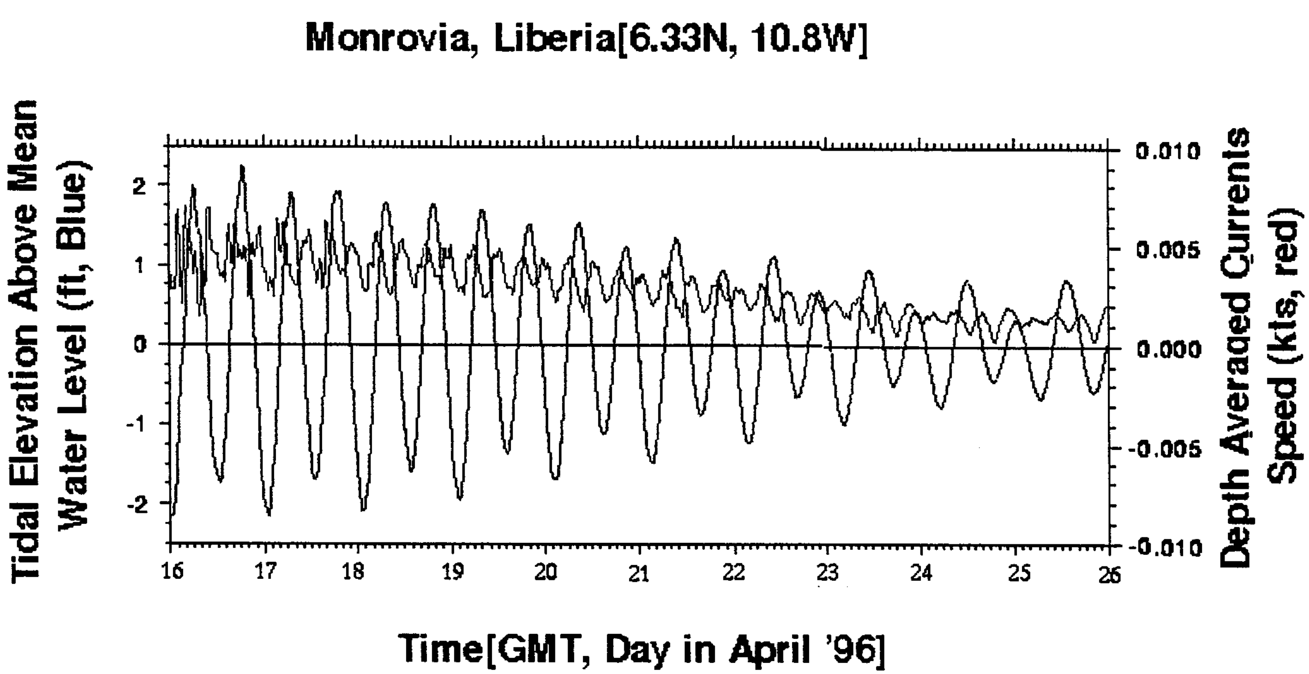
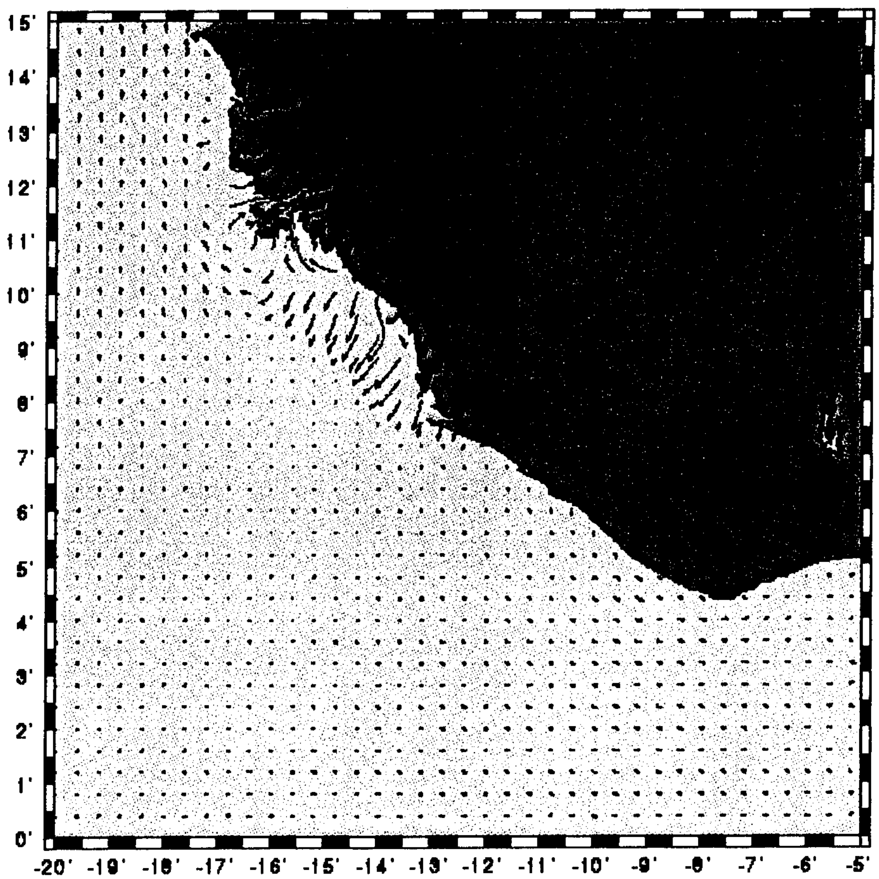


Figure 3. Time Series plots for Monrovia (Coarse Grid)

CURRENTSS Model

[Astronomical Tides]

Date = 16 Apr96 20 Hr



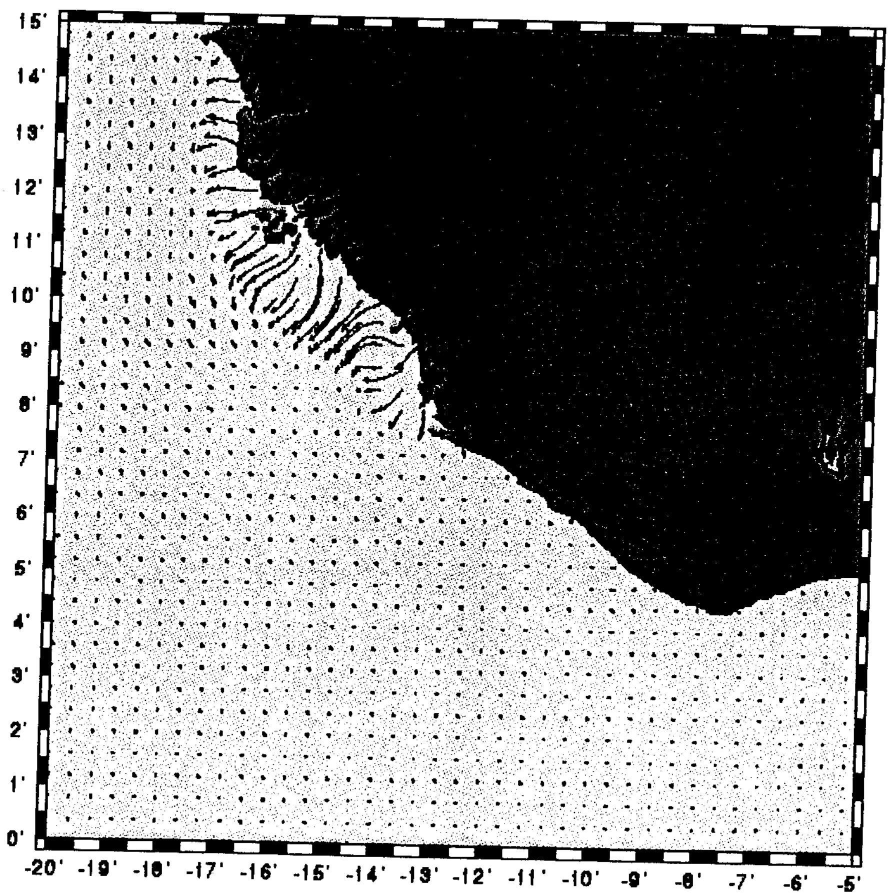
Currents

Figure 4. Streak–Plot of Tidal Currents for Coarse Grid Domain for 16 April.

CURRENTSS Model

[Astronomical Tides]

Date = 17 Apr96 00 Hr



Currents

Figure 5. Streak-Plot of Tidal Currents for Coarse Grid Domain for 17 April.

4.3.2 Coarse Grid

After completing the coarse grid run, the model was run for an identical duration for the nested high resolution grid. Once again, only astronomical forcing was provided and the same seven tidal components were included.

Time series data was saved at four locations: Sheather Rock (7.73° N, 12.78° W) in Sierra Leone, Kasi (7.05° N, 11.8° W), Monrovia and Little Kola (5.65° N, 9.85° W) in Liberia. Once again, the semi-diurnal tidal components were found to dominate the tides (Figs. 6 – 9). The maximum tidal heights occur at Sheather Rock, in Sierra Leone, in excess of 3 ft. At Little Kola, in Liberia, the maximum tidal heights were less than 2 ft. As seen earlier in the coarse grid results, the tidal currents are also maximum (approx. 0.021 kts) at Sheather Rock. Overall, the results from both coarse and fine grids were found to be very consistent in magnitudes and temporal variations.

Information for streak plots for tidal currents was again saved at every half hour interval. A few samples of these around Monrovia are shown in Figs. 10 – 12 for April 20th. Maximum tidal currents at low tide occurred at 0200 hours GMT until a Flood stage was achieved at 0750 hours GMT at Monrovia. Thereafter, maximum tidal currents occurred again at 0900 hours GMT for high tide: During this Flood event, the maximum magnitude of tidal height was about 1.7 ft and that of current was 0.08 kts. As expected, the fine grid results allowed more detailed features of tidal currents to be resolved, however, magnitudes were not significantly different.

4.4 Results (With Wind and Pressure Forcing)

4.4.1 Coarse Grid

The only surface forcing (from Meteorological models) available for the region of interest and time-frame was from global NOGAPS at 1.25° resolution. The CURReNTSS model was run for 3 days using the above surface forcing starting on April 15, 1996. Once again, the first day was treated as spin-up time and results predicted for the next 2 days for tides and storm surge. All the setup parameters were kept identical to those discussed in the previous section, except for the forcing which now included both, astronomical tides as well as winds.

Time series results for SSH and currents, with surface wind forcing, are presented in Figure 13 (Freetown) and Figure 14 (Monrovia). On comparing with Figures 2 and 3, wind forcing had only a marginal effect on sea level but increased the maximum magnitude of currents to 0.17 Kts (at Freetown) and 0.042 Kts (at Monrovia). The effect on currents

Prototype Tidal Model Elevation & Depth–Averaged Currents:

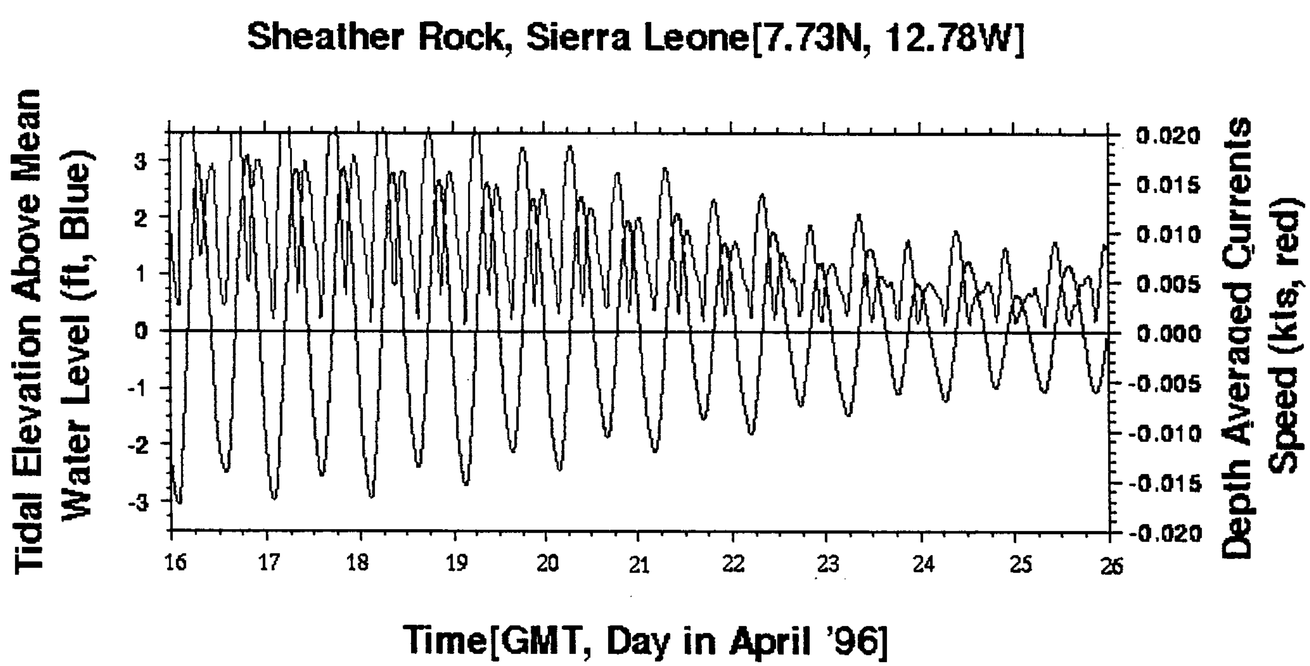


Figure 6. Time Series plots for Sheather Rock (Fine Grid)

Prototype Tidal Model Elevation & Depth–Averaged Currents:

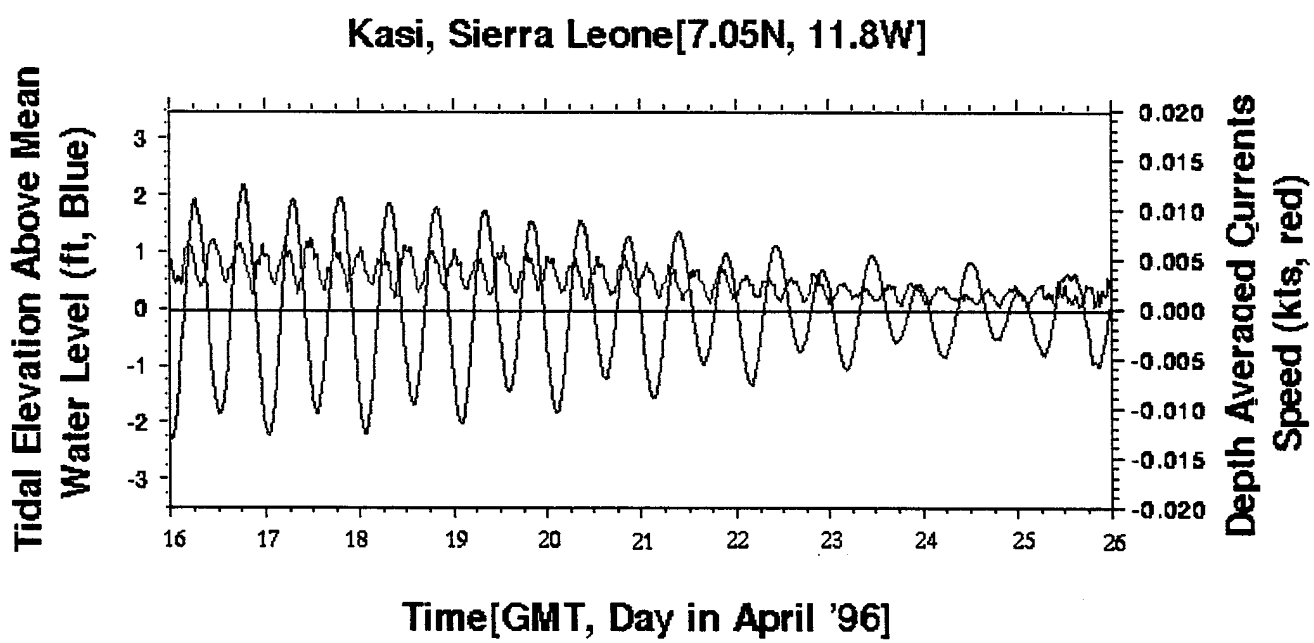


Figure 7. Time Series plots for Kasi (Fine Grid)

Prototype Tidal Model Elevation & Depth–Averaged Currents:

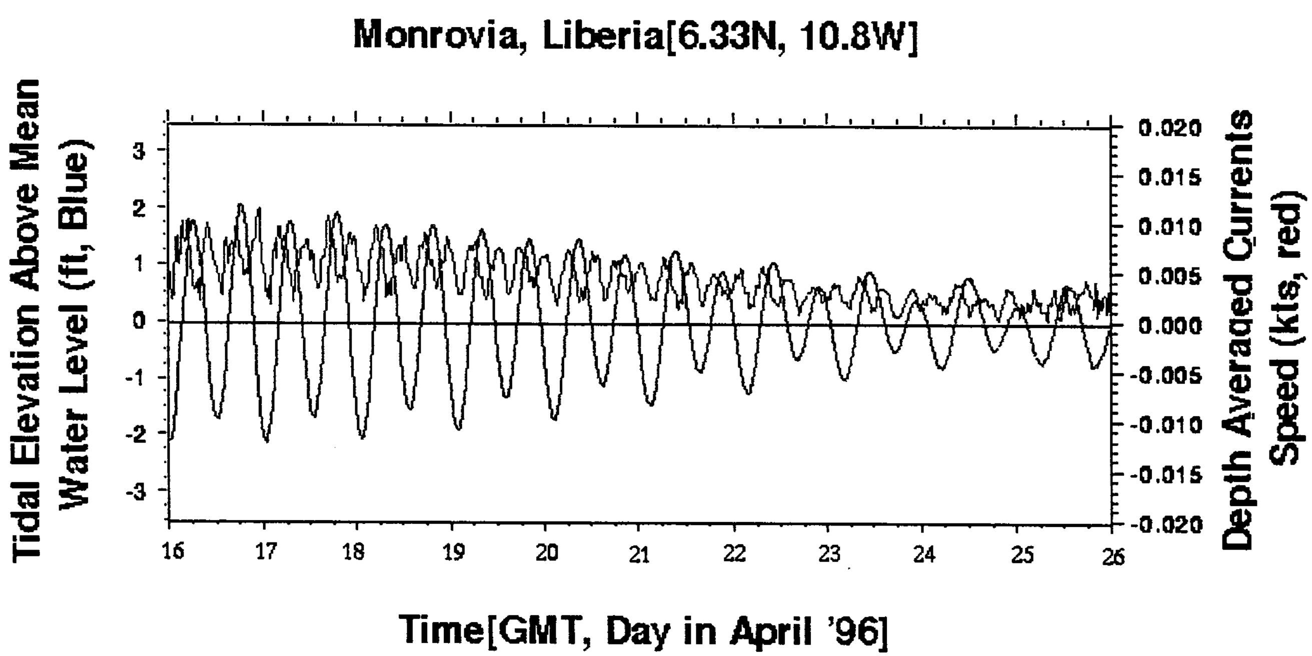


Figure 8. Time Series plots for Monrovia (Fine Grid)

Prototype Tidal Model Elevation & Depth-Averaged Currents:

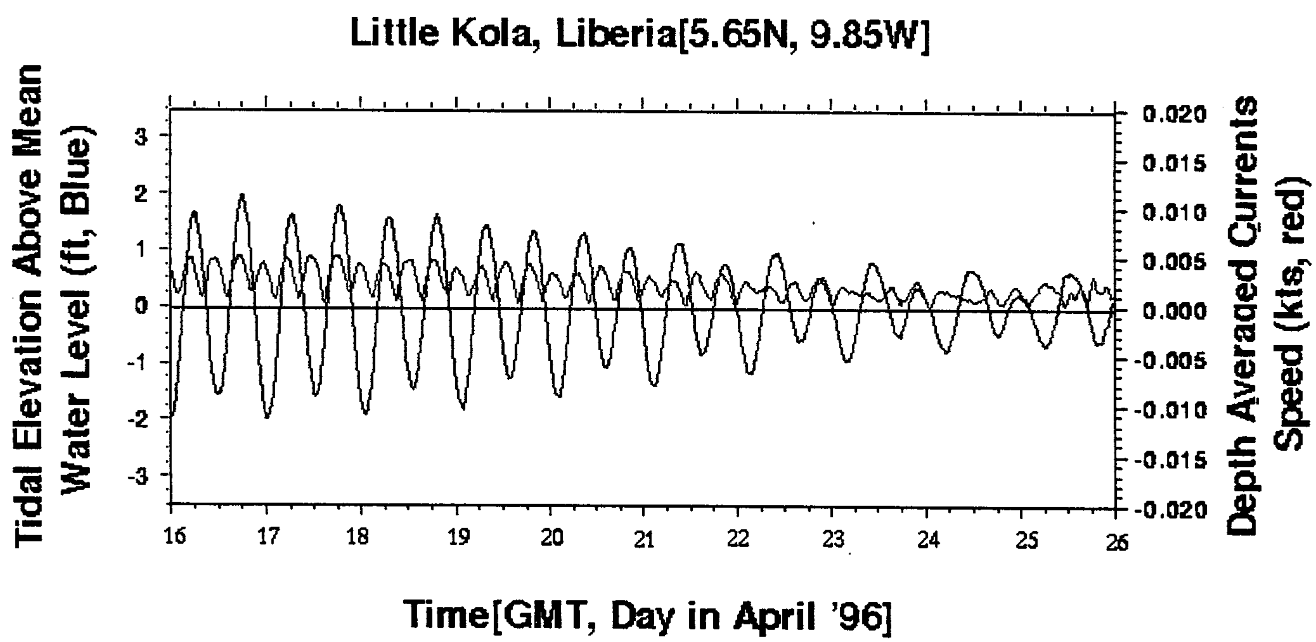


Figure 9. Time Series plots for Little Kola (Fine Grid)

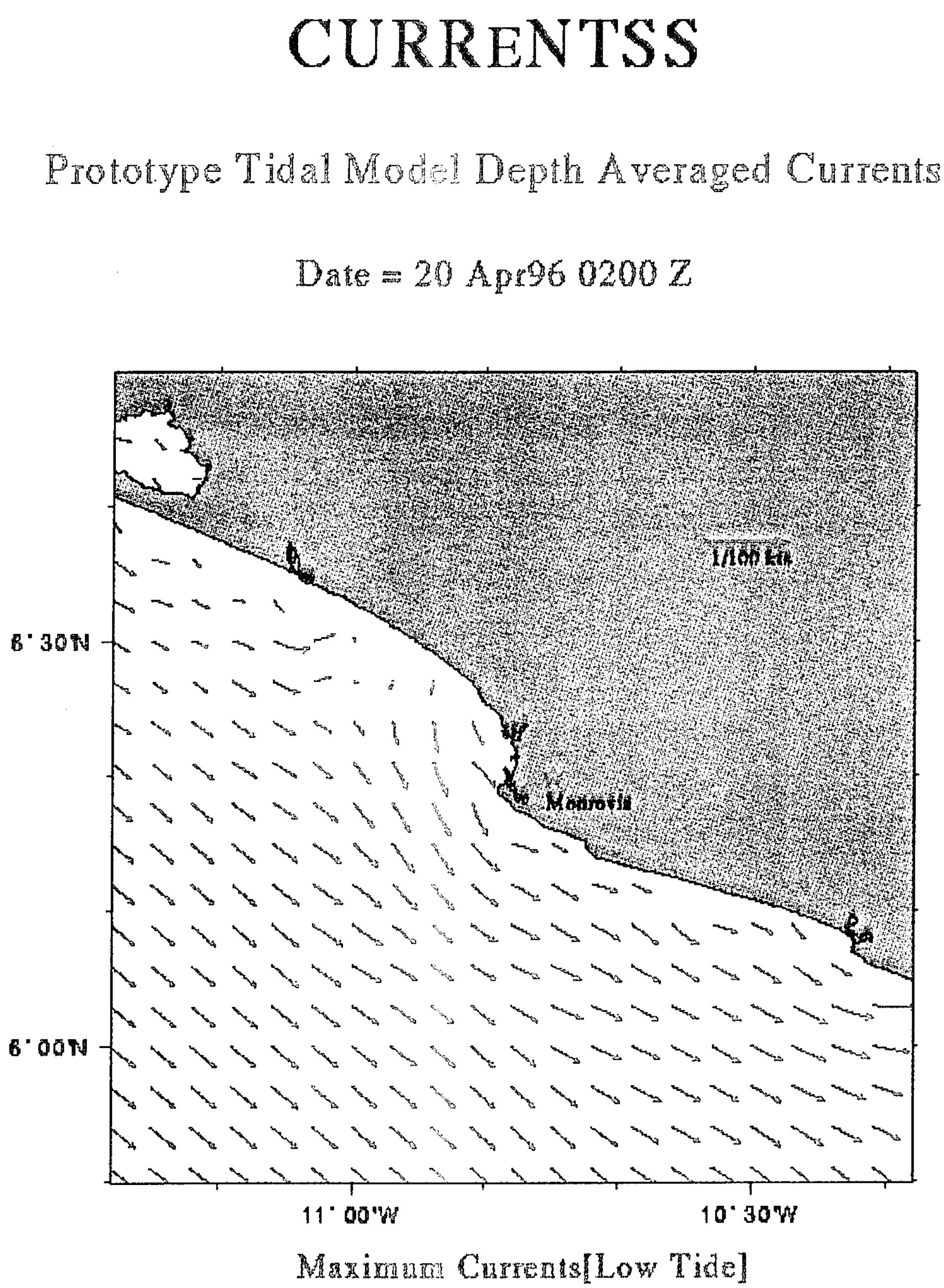
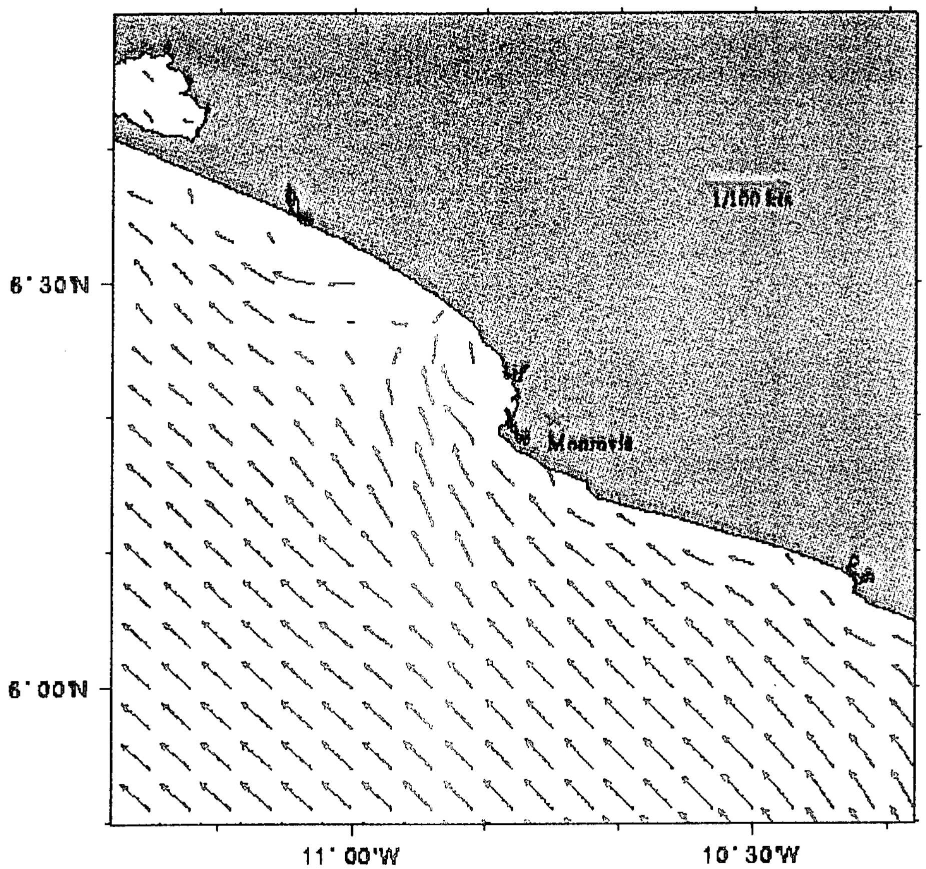


Figure 10. Maximum Currents at Monrovia at Low Tide (Fine Grid)

CURRENTSS

Prototype Tidal Model Depth Averaged Currents

Date = 20 Apr96 0750 Z



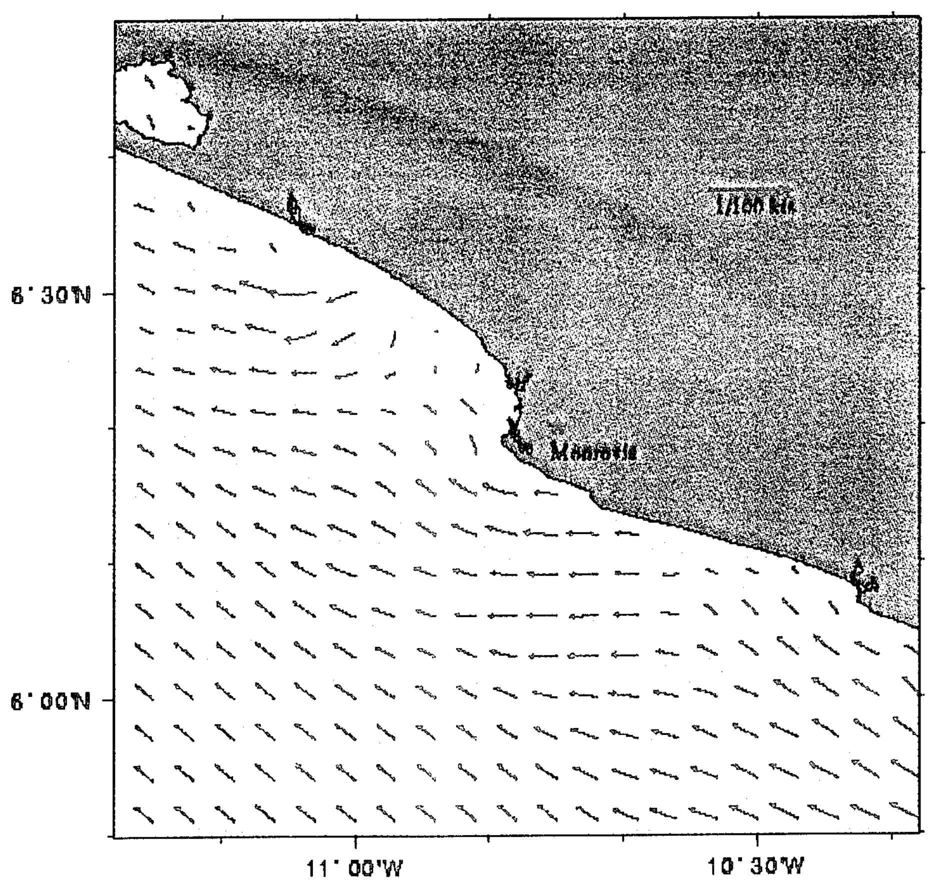
Maximum Currents[Flood]

Figure 11. Tidal Currents at Monrovia at Flood.
(Fine Grid)

CURRENTSS

Prototype Tidal Model Depth Averaged Currents

Date = 20 Apr96 0900 Z



Maximum Currents[High Tide]

Figure 12. Maximum Currents at Monrovia at High Tide.
(Fine Grid)

Prototype Tidal Model Elevation & Depth Averaged Currents with Surface Wind Forcing

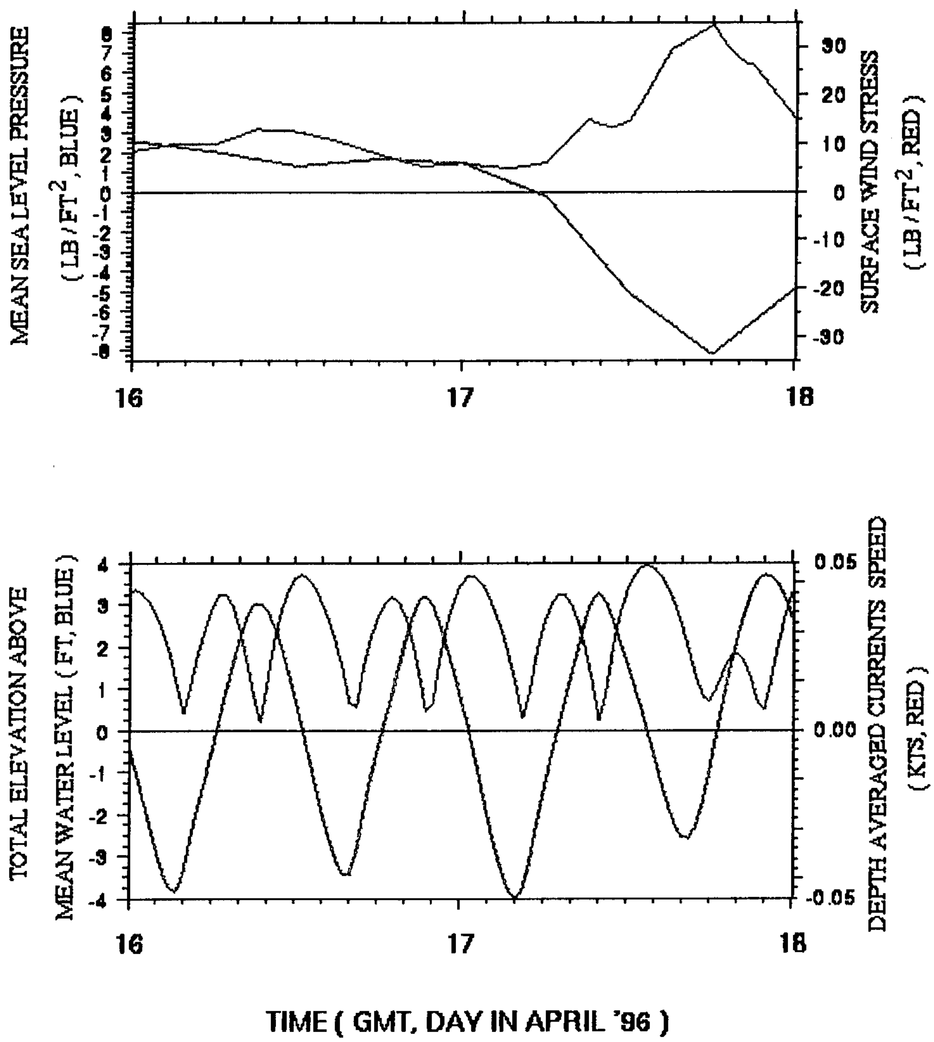


Figure 13. Time Series plots for Freetown (Coarse Grid)

Prototype Tidal Model Elevation & Depth Averaged Currents with Surface Wind Forcing

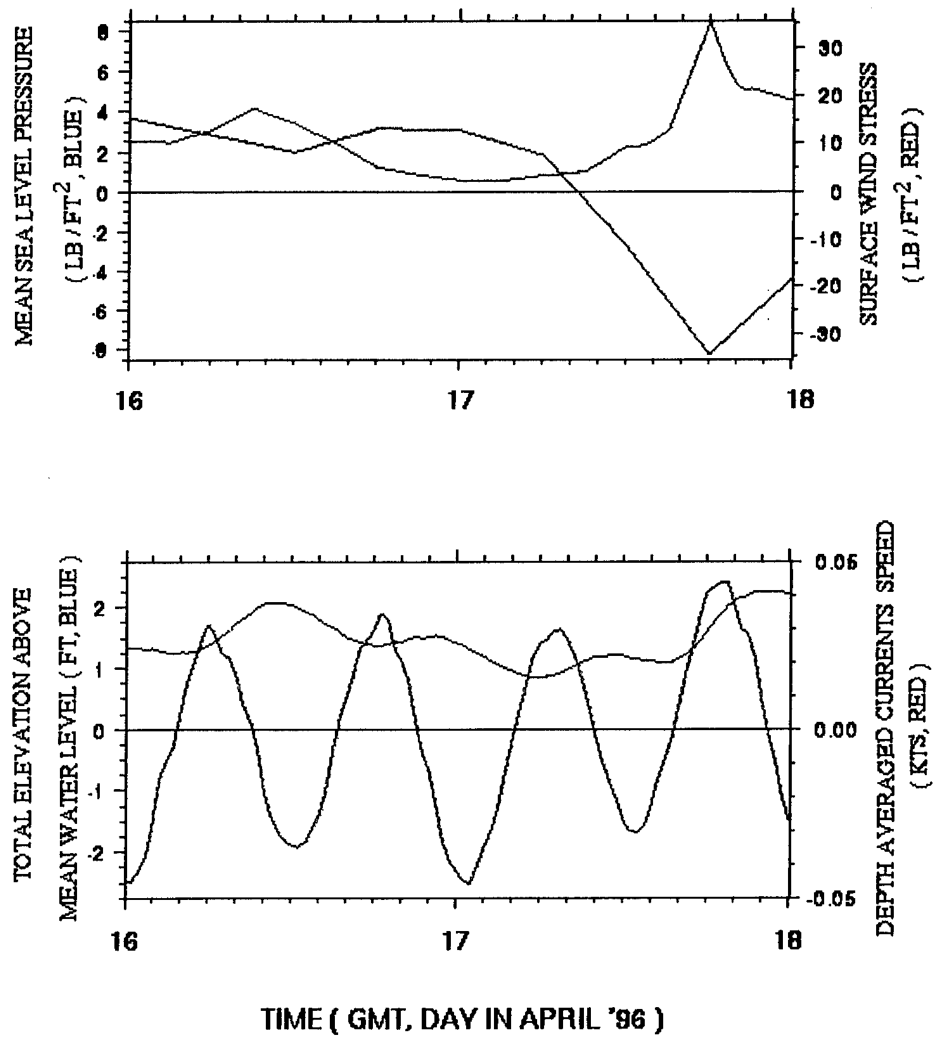


Figure 14. Time Series plots for Monrovia (Coarse Grid)

at Monrovia (increase of almost 425 %) was much greater than at Freetown (increase of 9%). Though the magnitude and variation of wind stress at the two locations were similar, significant increase in barotropic currents at Monrovia due to winds was because of much smaller currents produced there due to the astronomical tides alone. Tides continue to be dominated by their semi-diurnal constituents.

Figures 15-16 show a few sample streak plots for the resultant barotropic currents with wind forcing for the coarse grid domain.

4.4.2 Fine Grid

As before, after completion of the coarse grid model run with wind forcing, the fine grid model was run successfully for 3 days starting from April 15, 1996. All setup parameters were once again kept the same, except for the forcing which now included wind stresses. Time series outputs at the four locations (Sheather Rock, Kasi, Monrovia and Little Kola) are presented in Figs. 17 –20.

The sea level was found to be higher because of winds at all the above locations, with the maximum height occurring at Sheather Rock (about 3.6 feet) on April 17 (Figure 17). The tidal currents also increased significantly with maximums occurring on 17 April (at Kasi and Monrovia) of about 0.06 Kts. These maximums correspond to the time of maximum wind stresses (and minimum pressures) occurring on April 17 (see Figures 18 and 19). On comparing with results from astronomical tidal forcing alone (Figs. 6 – 9), the phases and amplitudes of sea level were similar in their temporal variations, unlike the tidal currents which showed substantial differences in both phases and amplitudes.

Streak plots for movie animations of tidal currents for the nested grid were also generated and saved every half-hour. A few snapshots are shown in Figs. 21 – 22.

5. PROBLEMS ENCOUNTERED AND SUGGESTED REMEDIES FOR THE FUTURE

The above case study demonstrates a real time operational capability for predicting sea level and vertically averaged currents in any region of interest around the world using the CURReNTSS model. Using this approach tidal heights and currents can be predicted for any day in advance. Similarly, using FNMOC output, 2-day forecasts can be made of sea level and vertically averaged currents in any region, should a contingency arise. But a number of obstacles had to be overcome along the way which must be addressed, and the lessons learned thereof, implemented for the future.

These problems can be sub-divided into issues pertaining to the GUI environment and those relevant to the numerical model CURReNTSS. A few others, unrelated to either of the above, are also discussed.

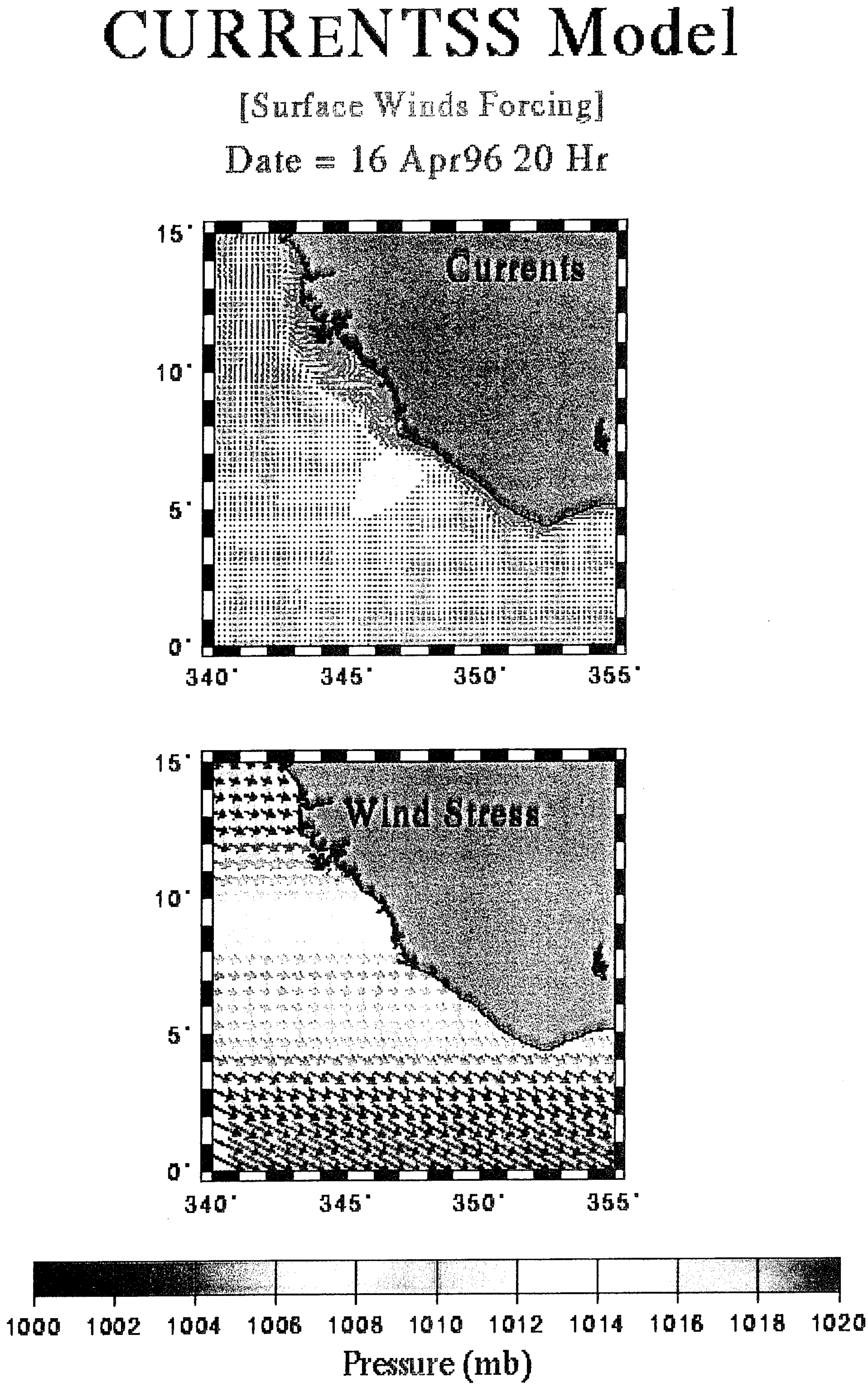


Figure 15. Streak–Plot of Tidal Currents for Coarse Grid Domain

CURRENTSS Model

[Surface Winds Forcing]

Date = 17 Apr96 00 Hr

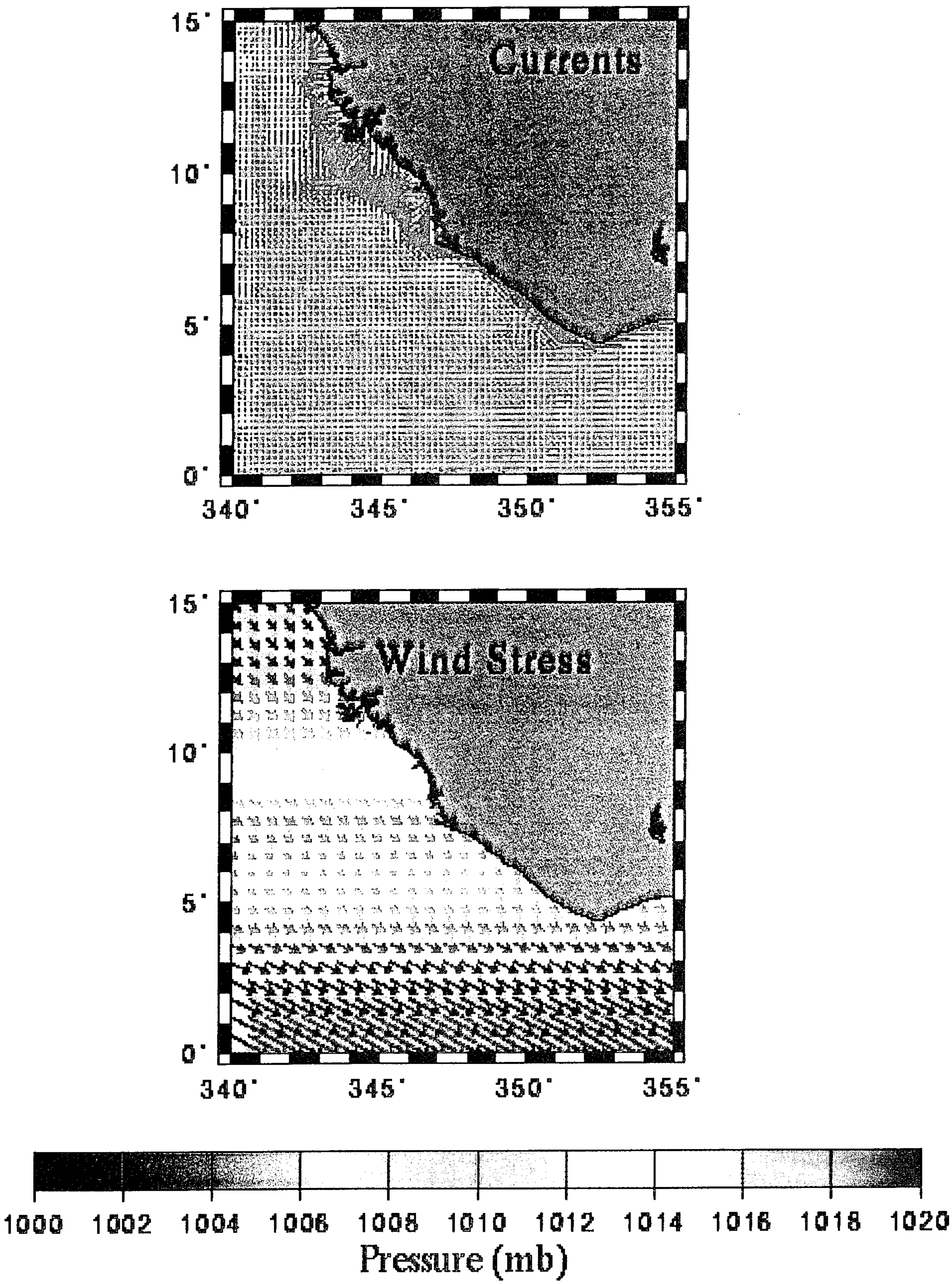


Figure 16. Streak–Plot of Tidal Currents for Coarse Grid Domain

Prototype Tidal Model Elevation & Depth Averaged Currents with Surface Wind Forcing

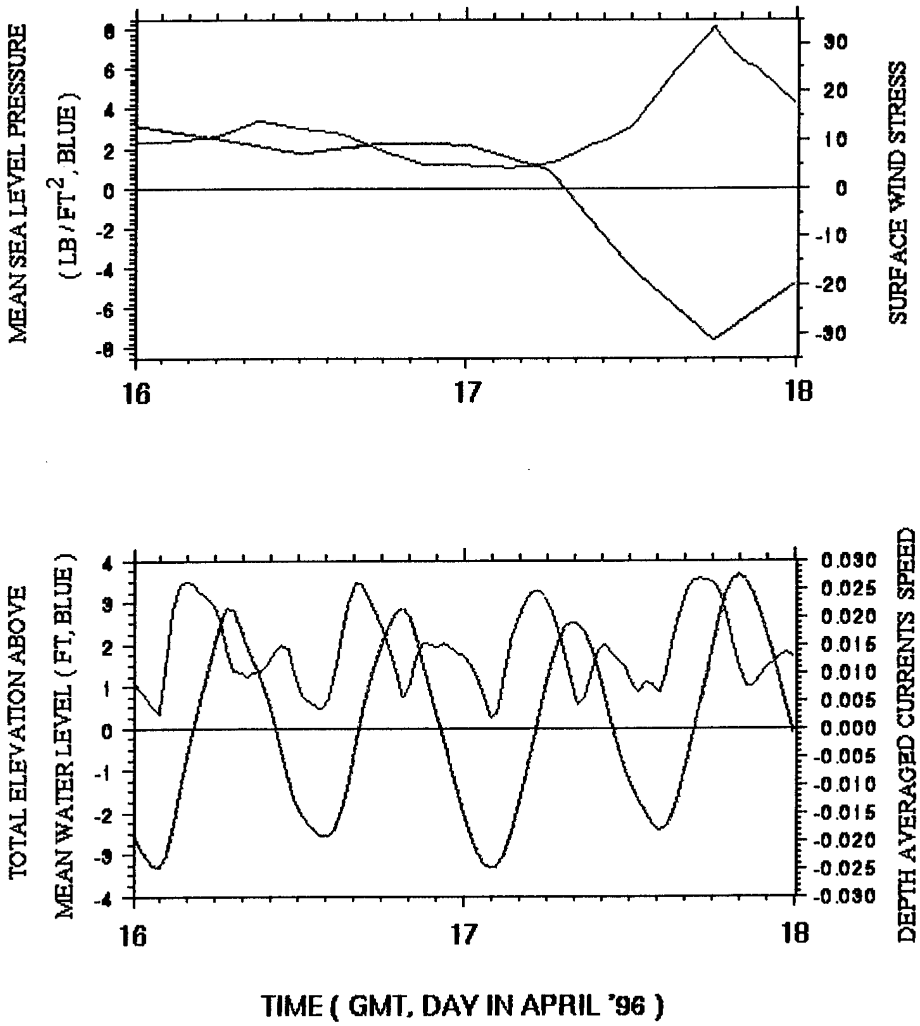


Figure 17. Time Series plots for Sheather Rock (Fine Grid)

Prototype Tidal Model Elevation & Depth Averaged Currents with Surface Wind Forcing

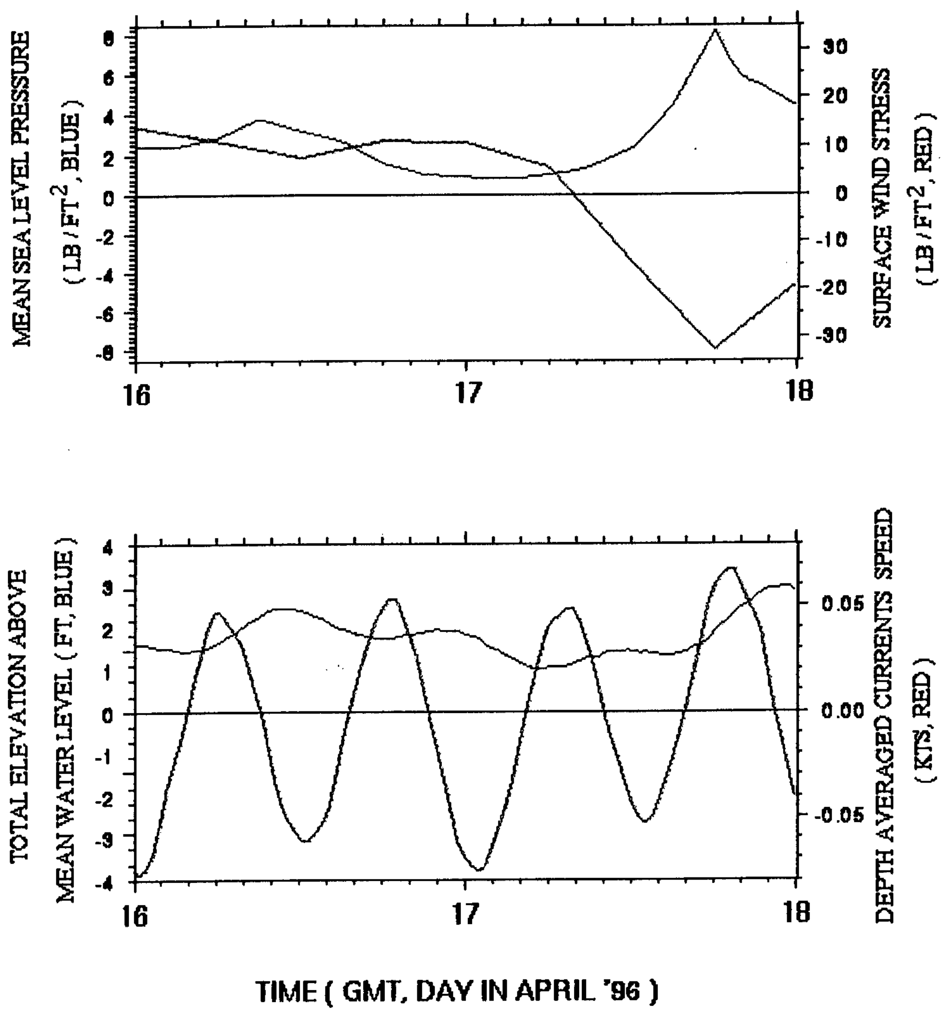


Figure 18. Time Series plots for Kasi (Fine Grid)

Prototype Tidal Model Elevation & Depth Averaged Currents with Surface Wind Forcing

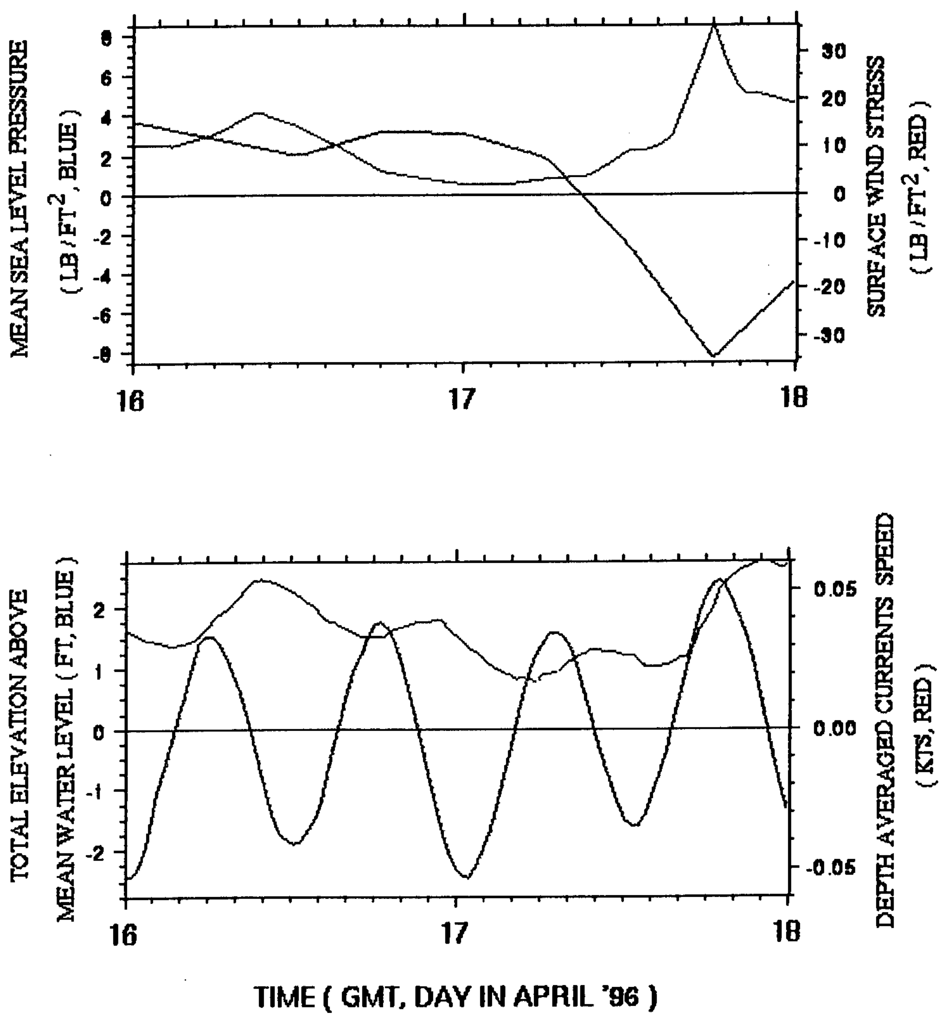


Figure 19. Time Series plots for Monrovia (Fine Grid)

Prototype Tidal Model Elevation & Depth Averaged Currents with Surface Wind Forcing

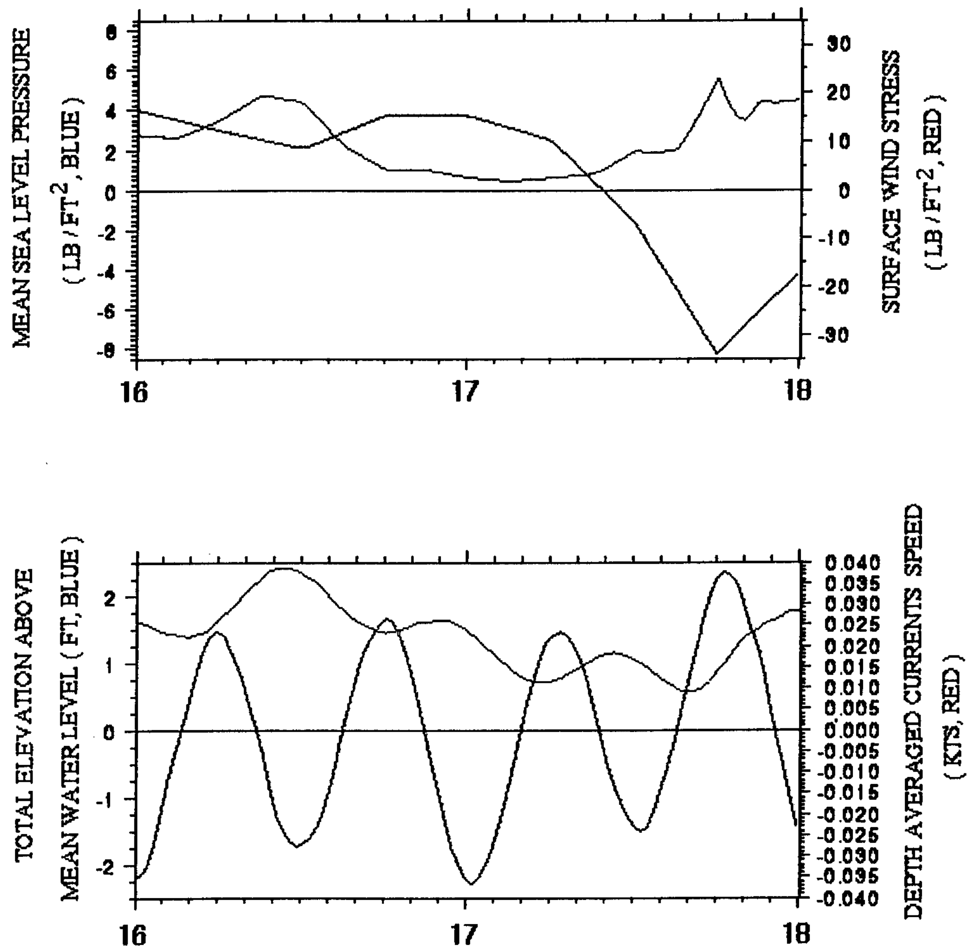


Figure 20. Time Series plots for Little Kola (Fine Grid)

CURRENTSS Model

[Surface Winds Forcing]

Date = 16 Apr96 20 Hr

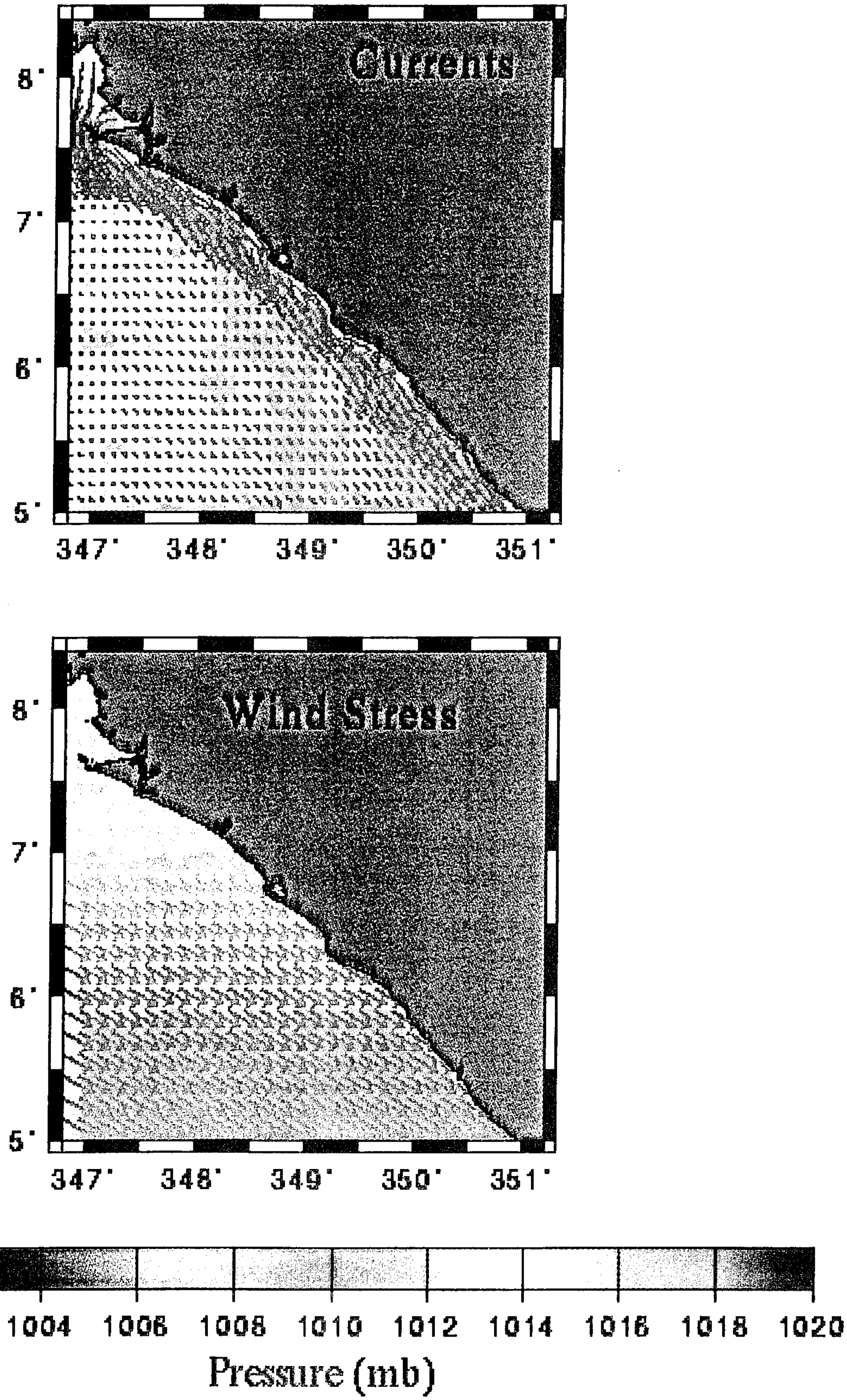


Figure 21. Streak–Plot of Tidal Currents for Fine Grid Domain

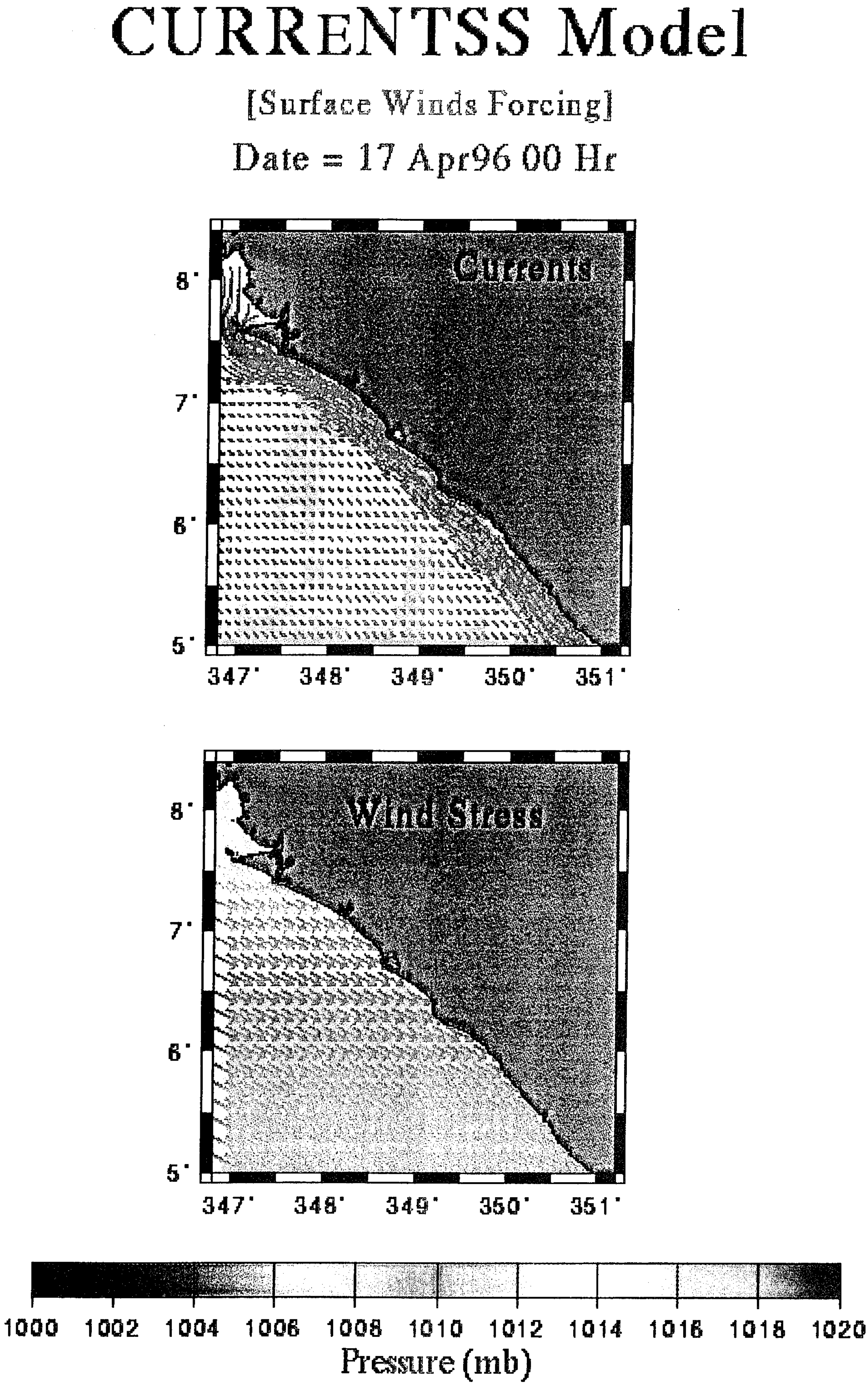


Figure 22. Streak–Plot of Tidal Currents for Fine Grid Domain

5.1 GUI Issues

- Pertaining to the bathymetry for the high resolution (1/20°) nested grid, the interpolations from DBDB5 database resulted in significant discrepancies in not only the bottom depths but also between the modeled coastline and the physical coastline (of the order of 10km). A better resolved and more accurate bathymetry database in the GUI will help alleviate this problem.
- Tidal station database must be expanded to include any recent observed tidal constituents data.
- Significant effort was required to set up the forcing fields for the storm surge prediction. A standardization for available (both current and future) surface forcing fields from meteorological models with regards to formats (filenames, data and projections) would help streamline the process.
- Post-processing options in the GUI must be expanded to generate results ready for immediate operational support (input in this regard from NAVOCEANO/WSC would be helpful).
- A "help" index explaining all the various options available to a novice GUI user needs to be added.

5.2 Model Issues

- The CURReNTSS model uses a simple data assimilation procedure. It may be useful to explore a more sophisticated assimilation scheme based on optimal interpolation.
- The results presented in Section 4.3 did not include any long term (equilibrium) tides or nodal factors for astronomical forcing which are easily added to the model. While the former are considerably small and can be neglected, the latter can influence results more significantly. The information on nodal factors is readily available from Admiralty tables on a monthly basis.
- No data were available for verification of the 2-day sea level and current forecasts off the coast of Liberia. However, tidal sea levels and currents appear to be reasonably well simulated.
- In future work, the CURReNTSS model, a sub-component of the 3D NAVOCEANO/CU operational model, will be enhanced to perform 3-D simulations that include tides and tidal currents. The 3-D model would be more suitable to obtain accurate tidal currents in the entire water column (i.e including baroclinic component) using the same methodology.

5.3 Miscellaneous

- On the second day of the operational case study, the network went down disrupting communications between CAST and CU.
- On the third day, one of the file servers at CAST was accidentally damaged. All the relevant files for the model had to be transported to a stand-alone workstation.

The above problems led to unavoidable delays during the operation. But the lessons learned will help eliminate them in the future and expedite the total operation by approximately 50%.

6. CONCLUDING REMARKS

Responding to a NAVOCEANO request to provide support in predicting tidal heights and currents for the Liberian coast, MSU CAST and CU, in a joint effort, implemented the CURReNTSS model in the region to produce operationally useful products within four days from the time of request. This demonstration shows that:

- The analysis of the operations indicates that this time can be significantly cut. The **ultimate goal of relocating the model to any region in the world and obtaining products within 48 hours is readily attainable.**
- While regular collaboration and communication among NAVOCEANO, CAST and CU played an important role in obtaining the needed results in a short time, more precise specifications on NAVOCEANO desired products would be needed for an efficient implementation of the model in the future .
- The quality of operational products depends to a large extent on the availability of accurate, fine-resolution data bases such as bathymetry/hydrography data sets and wind forcing (NORAPS/COAMPS). It is recommended that NAVOCEANO establish these data bases for high-risk regions in advance so that potential operational numerical models can be relocated successfully and efficiently. For emergency situations where a high resolution data base is not already available, an appropriately trained tiger team should be established to derive the required fine-resolution data sets for any region in a short time frame.
- The real-life application of the CURReNTSS model to a contingency situation provided useful information on its rapid relocatability, real time operation capability, and robustness. However, some additional work is needed on model parameter specification and the graphical user interface. Research and operations personnel at NAVOCEANO WSC, Code N531, and MSU CAST should determine the details.

- The exercise of the model in a semi-operational mode has demonstrated that after some refinements it can be transitioned as an operational model. It is recommended that this transition be formalized, documented and started immediately.
- CAST is aware of the ADCIRC model capability at NAVOCEANO developed by the Army Coastal Engineering Research Center at Vicksburg, MS. Being a finite element model, it is relatively difficult to configure it in a new ocean region because of the additional effort and resources involved in generating the model grid. It is desirable that the CURRENTSS model and the ADCIRC model should be compared in a common environment where enough model evaluation data are available, to ascertain their strengths and weaknesses so that each may be employed most advantageously in a complementary mode.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the guidance and support provided by NAVOCEANO researchers, Drs. Robert Carter and Ted Bennett. Also, the case study could not have been a success without the timely help and combined effort from Yee Lau, James Corbin and Fabio delle Cese at CAST.

APPENDIX A: VALIDATION OF CURReNTSS MODEL NEAR SAN DIEGO

While the results from the relocatabie model for Liberia look reasonable, there were no data for verification of the results. Also no high resolution operational atmospheric model outputs were available for model forcing. This affected at least the high resolution sea level and current forecasts. To test the model skill when high resolution bathymetry and high resolution atmospheric forcing were available, the model was applied to the San Diego and Camp Pendleton regions off the west coast of the U.S. The principal consideration for selection of these domains was the availability of shake-down results from the triply-nested COAMPS atmospheric model off the west coast. The highest resolution results available were from the 5 km COAMPS grid. Therefore the coarsest CURReNTSS model domain was chosen to be the same as this domain, and the resolution also the same. A 500 m Camp Pendleton and 1 km San Diego Bay nested domains were also chosen. Fortunately, high resolution bathymetry was also available for this region, so that a realistic simulation could be made. The results for Camp Pendleton were not as interesting as those for San Diego Bay and hence will not be presented here.

A1. Model Domains And Setup

A1.1 Coarse Grid

The domain for the coarse grid extended from 119.97 ° to 116.58° W and from 31.87° to 34.5° N (see Figure A1). The grid resolution was 5 km (selected to match the finest COAMPS output) resulting in a 64×59 grid. It covered the California coast including the cities of San Diego in the south to Santa Barbara in the north. The bathymetry was interpolated from an available high resolution database. The GUI provided data from 9 tidal stations in this region which were assimilated into the model with a fixed weighting parameter (0.9). The GUI was also used to set up the boundary conditions for the open boundaries, south and west, and only seven linear tidal constituents were included, namely M_2, S_2, N_2, K_2, K_1, P_1 and Q_1. The model was run with both the astronomical tides and with surface wind forcing (obtained from COAMPS) to predict tides and storm surge.

The external (barotropic) time step was 8 seconds. In all, 13 locations were chosen for saving time-series output for tidal heights and currents.

SWUS Model Domains

Camp Pendleton (~ 500m) San Diego Bay (~1 km)

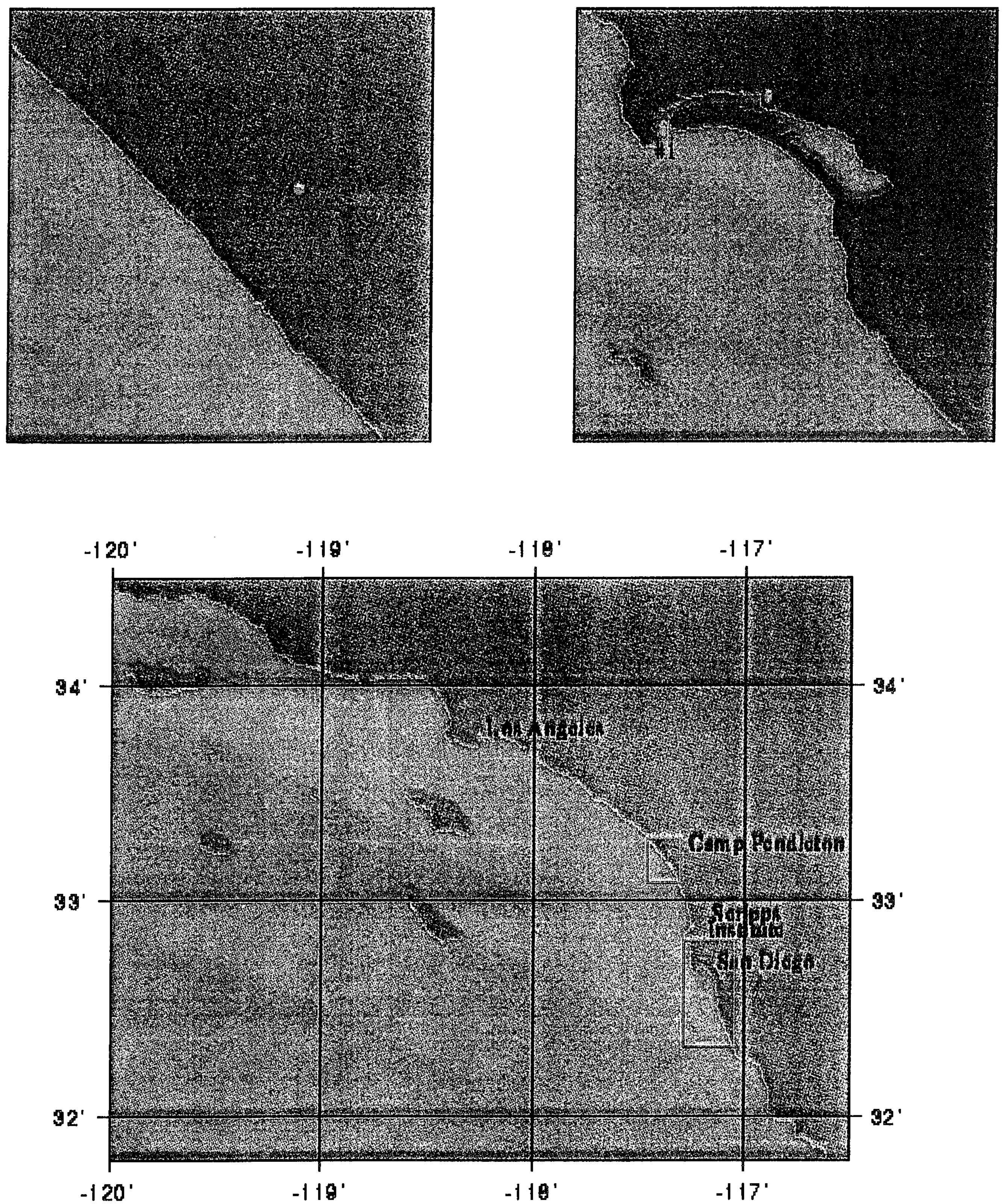


Figure A1.

A1.2 Fine Nested Grid:

The nested fine grid was centered around San Diego Bay at a resolution of 1 km, 117.28° to 117.03° West and 32.32° to 32.82° in the North (see Figure A1). The total number of grid points at this resolution was 24×57. The bathymetry was obtained similarly as above and no tidal station data were assimilated. The boundary conditions for the open boundaries were provided by the output of the coarse model run. Because of the higher resolution, the time step was reduced to 5 seconds. Time series output was saved at 5 different locations to compare results with the coarse model output.

A2. Results

The coarse (5 km) and fine (1 km) resolution models were run for Jan 2 – 15, 1995, with a one-day spin up both in the tides alone and tides plus storm surge modes. Figure A1 shows the domains for the two models. Figure A2 shows a comparison of the model-predicted and observed M_2 tide at 4 points along the coast of the coarse grid model (see Figure A1 for the locations of the points) from the tides only run, showing that the methodology employed provides reasonable results for tides. Note that these points were not assimilated into the model. Figure A3 shows the sea level time series at the same four points from the tides plus storm surge run as well as tides only run that included M_2, S_2, N_2, K_2, K_1, P_1 and Q_1 tides. O_1 was omitted because the data base did not have data on O_1 for assimilation. Nodal factors and long term tides were also ignored. The difference between the tides only and tides plus surge models showed the substantial influence of atmospheric forcing on sea level. However, even stronger influence would have been felt if the storm had not veered away from the region in a north-northeasterly direction instead of impacting the region head-on. Also, the tides were predominantly diurnal, modulated somewhat by semi- diurnal ones, as expected for the west coast of the U.S.

Figure A4 shows the time series of sea level pressure, wind stress, sea level and vertically integrated currents at one of these points. Results from this same point from the fine grid model will be presented later for comparison for surge only simulation (tides were omitted to bring out aspects of atmospheric forcing). Note the nearly inverse barometer response of sea level to atmospheric pressure forcing. Figures A5 and A6 show snap shots of vertically-averaged currents for two selected times during the model run. (Animations for the entire model run are available at MSU CAST). Note the strong current vectors which correspond to vigorous inertial oscillations. These are well-correlated with topographic features resolved because of the high resolution bathymetry used in the model.

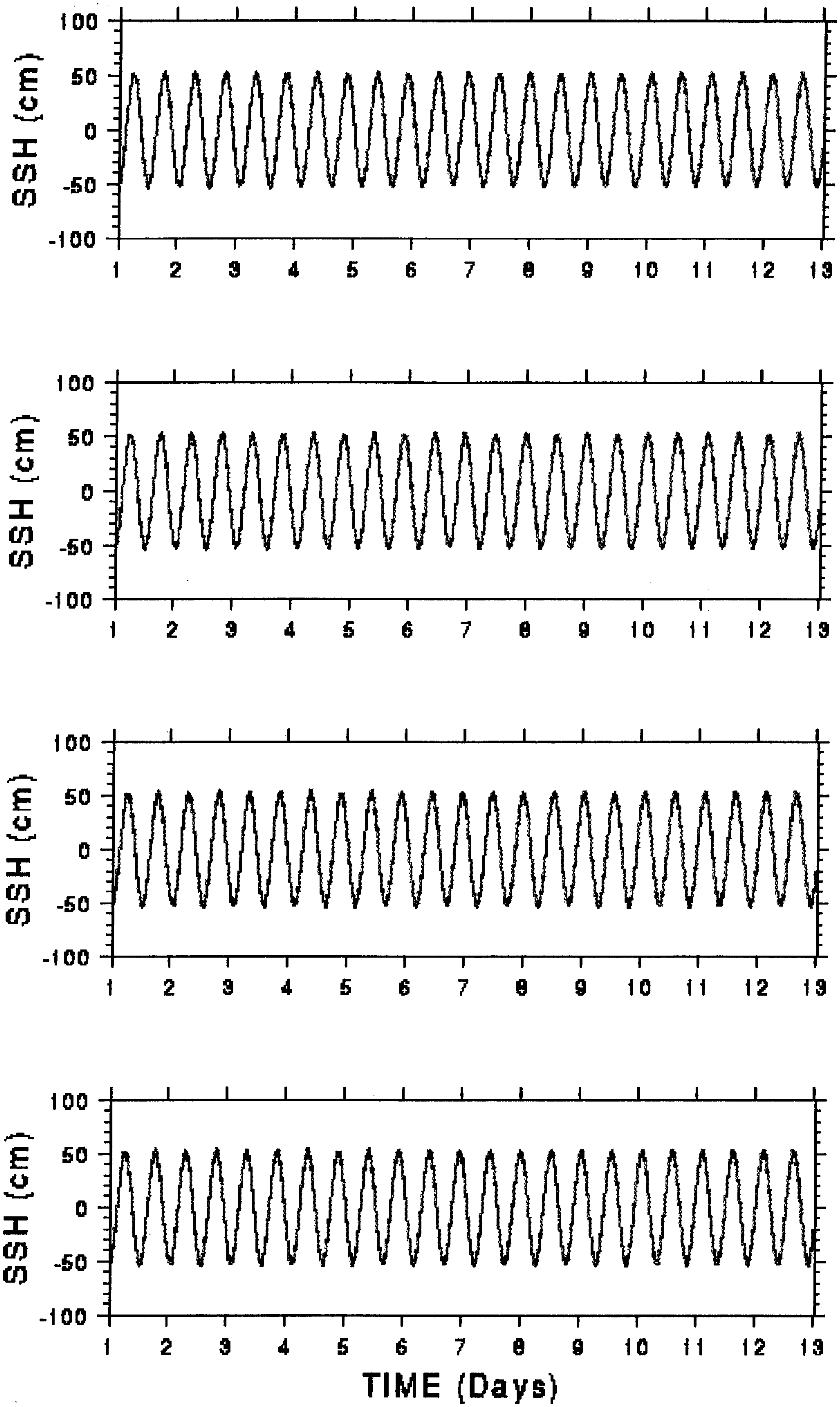


Figure A2.

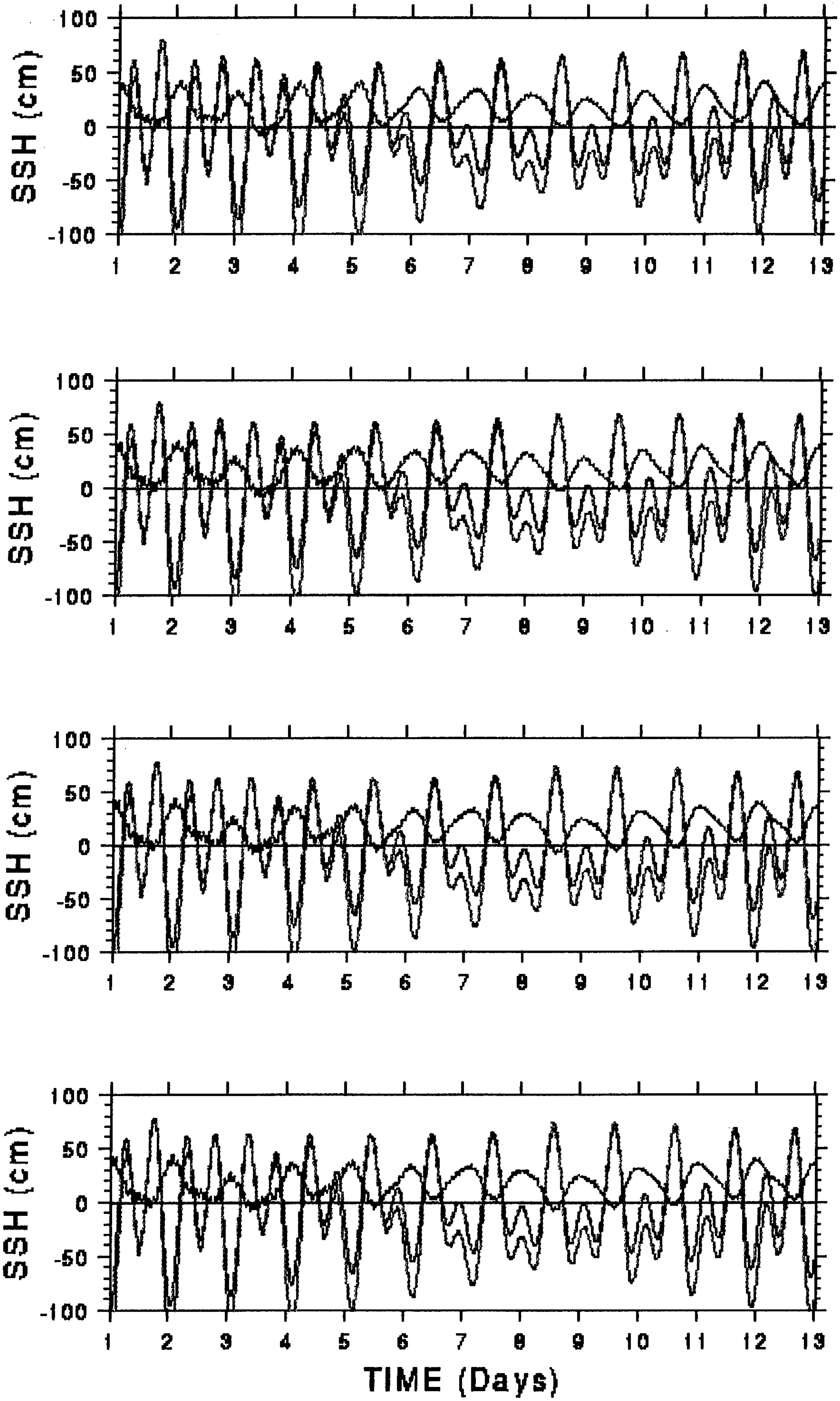
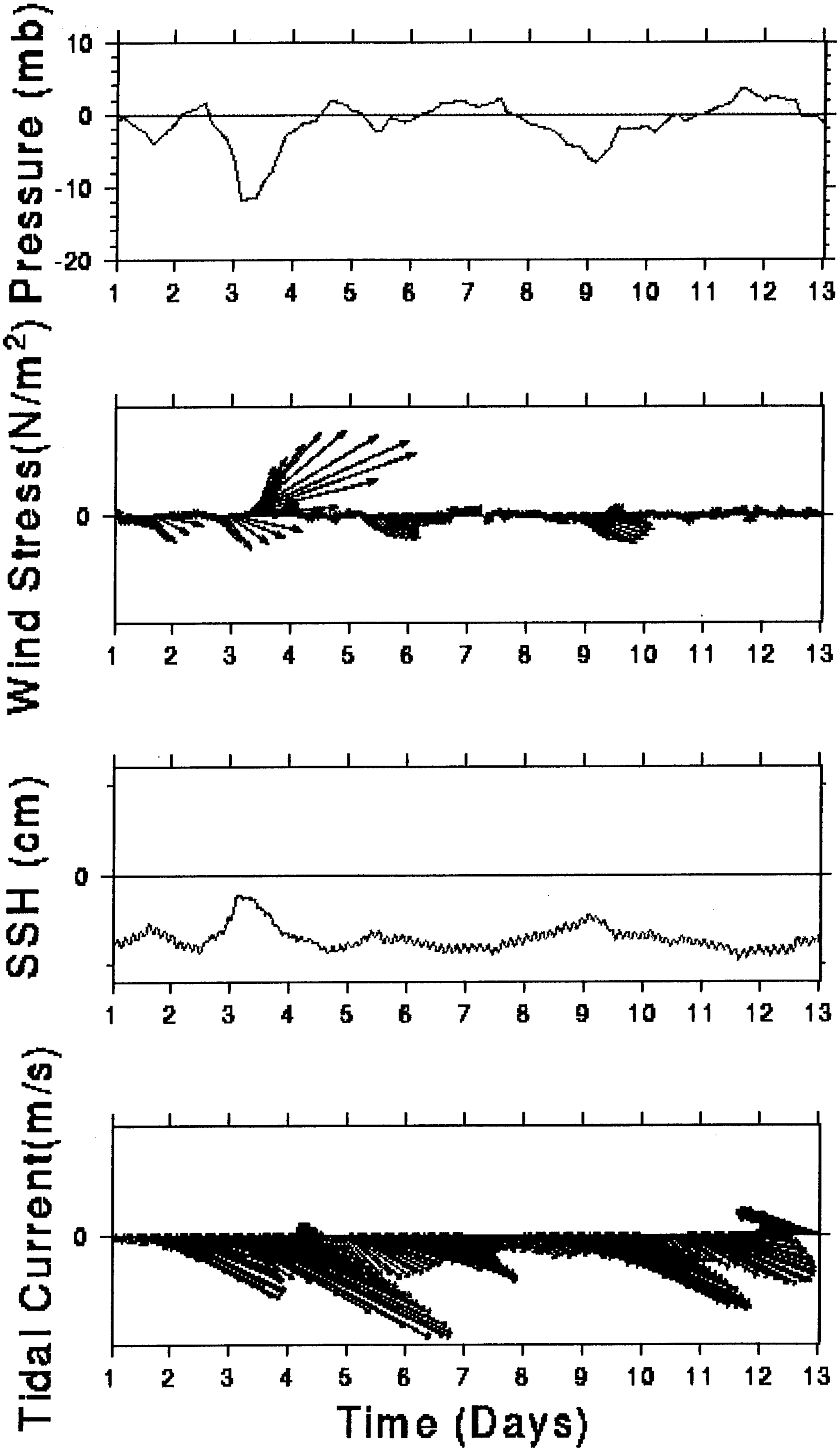


Figure A3.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10
0
-10
-20
Wind Stress(N/m2)
0
SSH (cm)
0
Tidal Current(m/s)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Time (Days)

Figure A4.

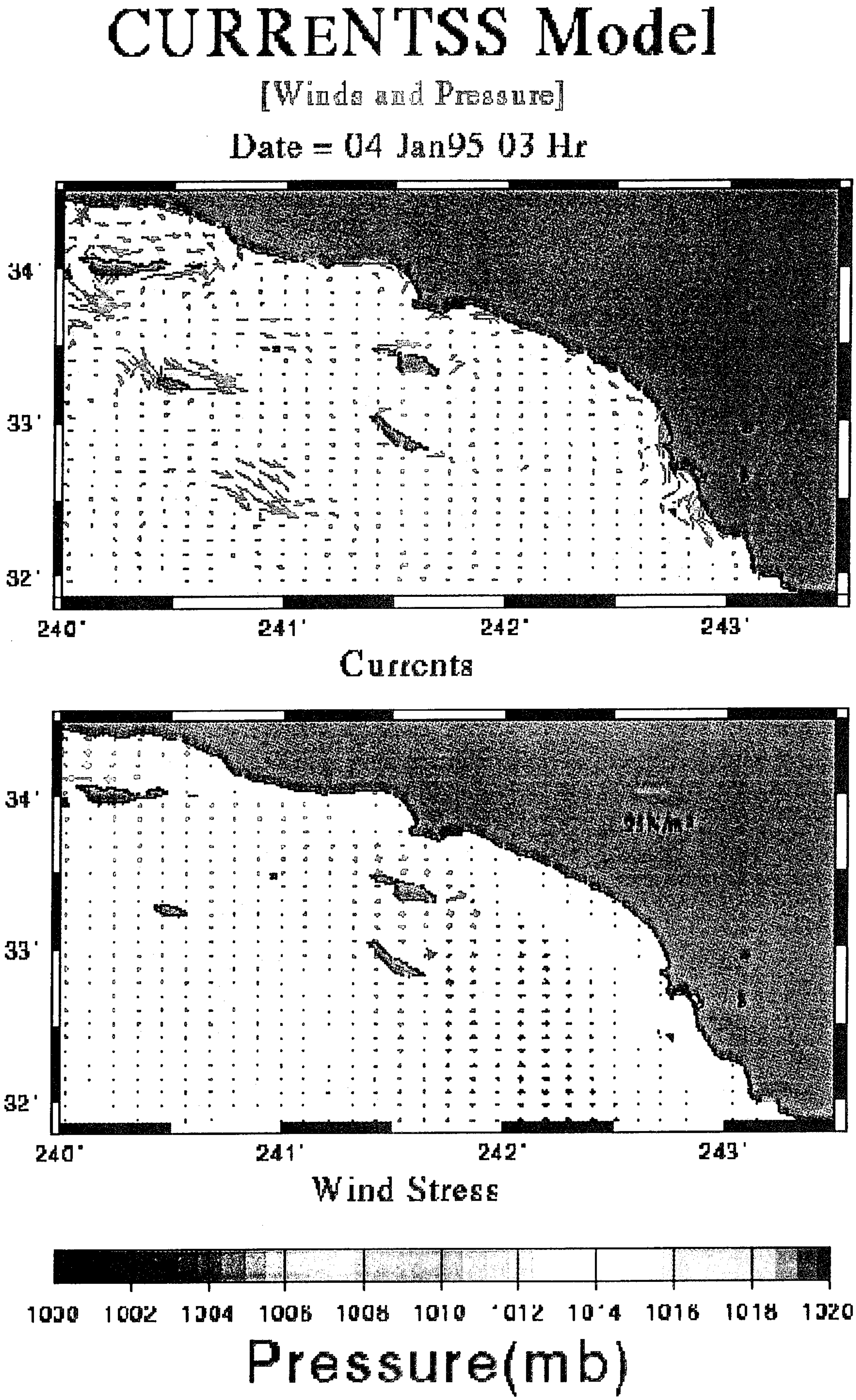

CURRENTSS Model
[Winds and Pressure]
Date = 04 Jan95 03 Hr
34°
33°
32°
240°
241°
242°
243°
Currents
34°
33°
32°
240°
241°
242°
243°
Wind Stress
1000
1002
1004
1006
1008
1010
1012
1014
1016
1018
1020
Pressure(mb)

Figure A5.

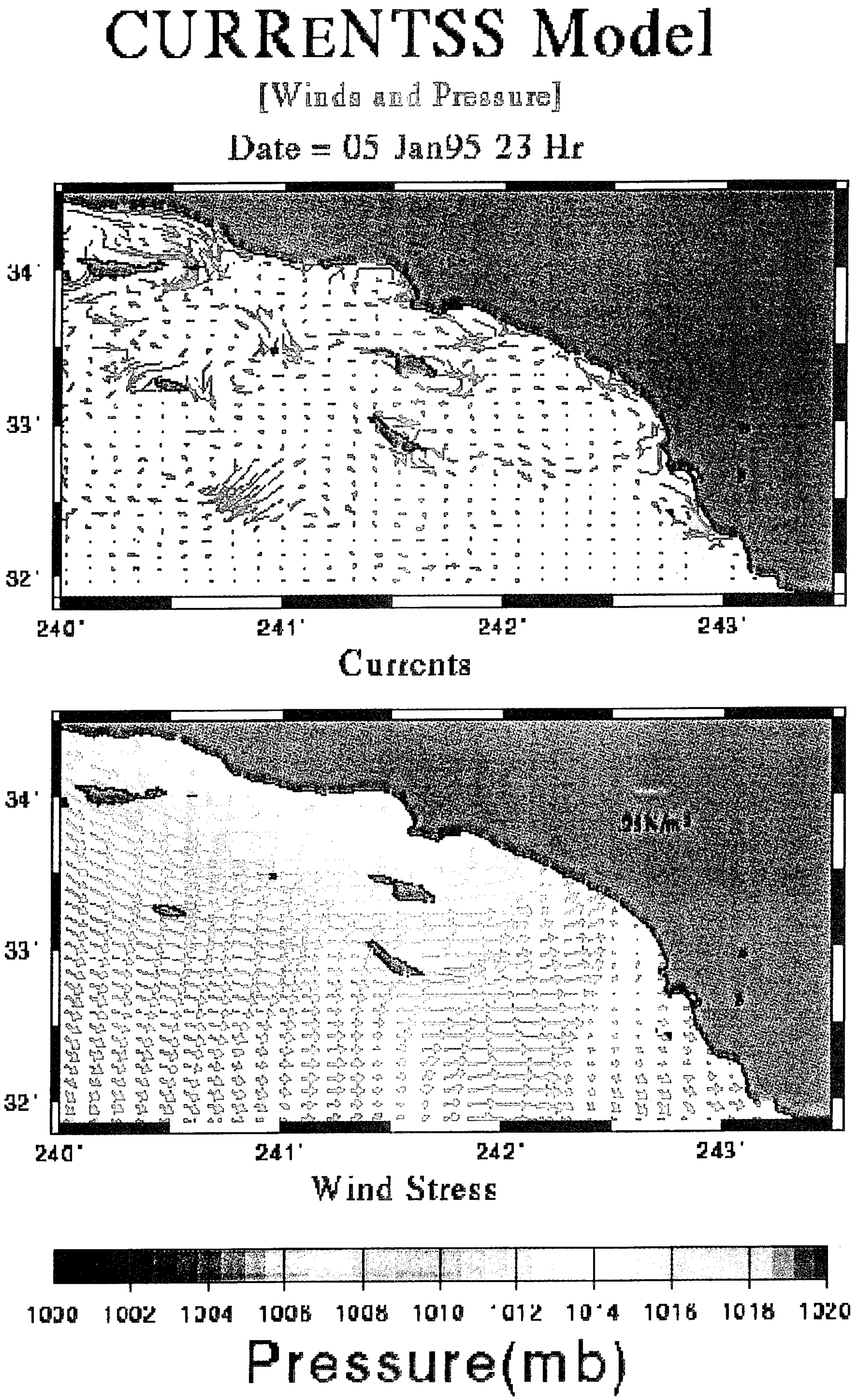

CURRENTSS Model
[Winds and Pressure]
Date = 05 Jan95 23 Hr
34'
33'
32'
240'
241'
242'
243'
Currents
34'
33'
32'
240'
241'
242'
243'
Wind Stress
1000
1002
1004
1006
1008
1010
1012
1014
1016
1018
1020
Pressure(mb)

Figure A6.

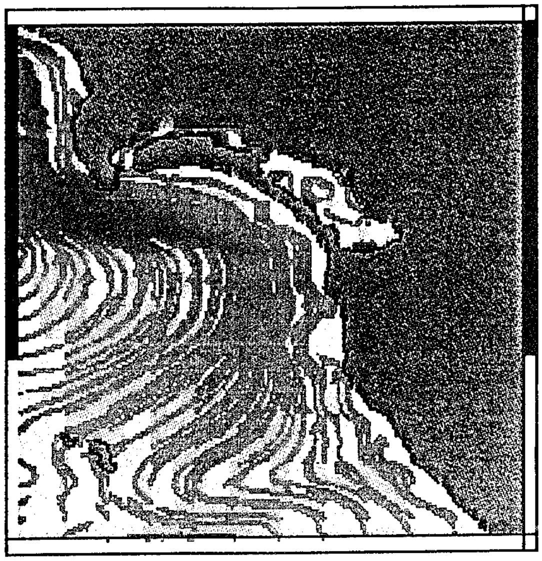
Figures A7 and A8 show the same results as Figures A5 and A6 but from the high resolution San Diego model run using the boundary conditions generated by the above coarse resolution model. The surface forcing is the same as that used in the coarse grid model, but interpolated to the fine grid. Note the small topographically-trapped eddy-like features (animations for the entire period of model simulation are also available at MSU CAST) captured by the model because of the accurate high resolution bathymetry available for the region. The high resolution also captures features in the fine resolution model not seen in the coarse resolution results.

Finally, Figure A9 shows time series at the point mentioned above, but from the fine resolution model. The results for sea level are similar to that obtained from the coarse resolution model, while the currents are stronger. This is as expected since unlike SSH, currents are influenced strongly by topographic features and hence the finer the topography resolved, the more accurate the currents are likely to be.

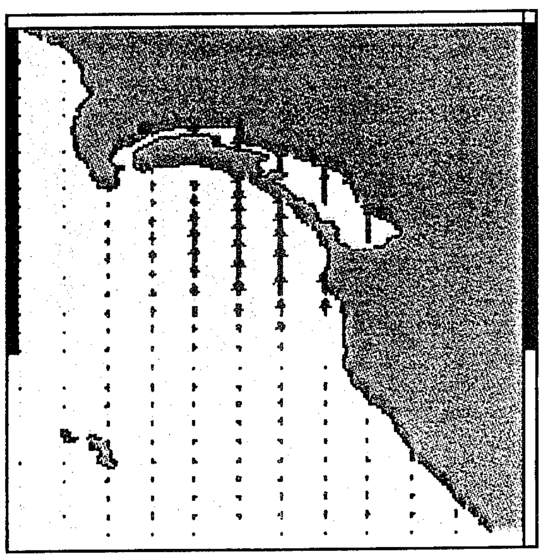
CURRENTSS Model

[Winds and Pressure]

Date = 04 Jan95 03 Hr



Currents



Wind Stress

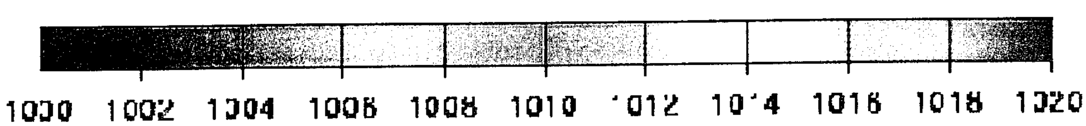


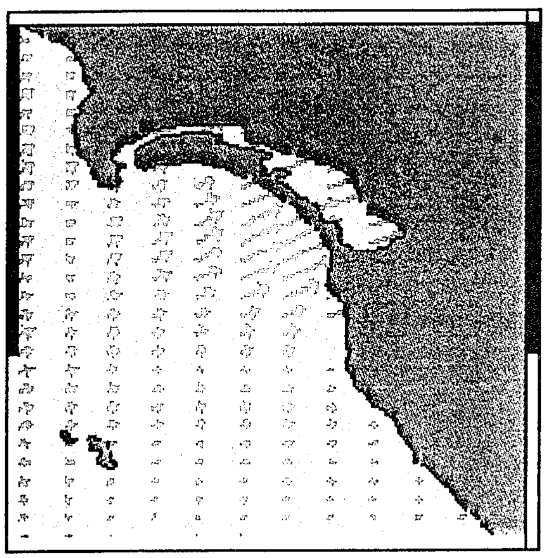
Figure A7.

CURRENTSS Model

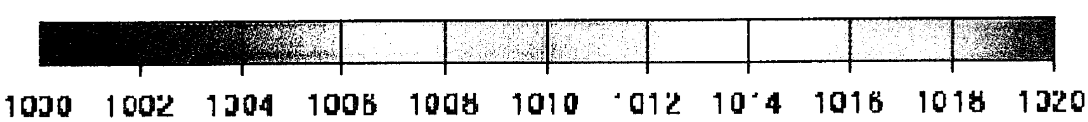
[Winds and Pressure]

Date = 05 Jan95 23 Hr

Currents

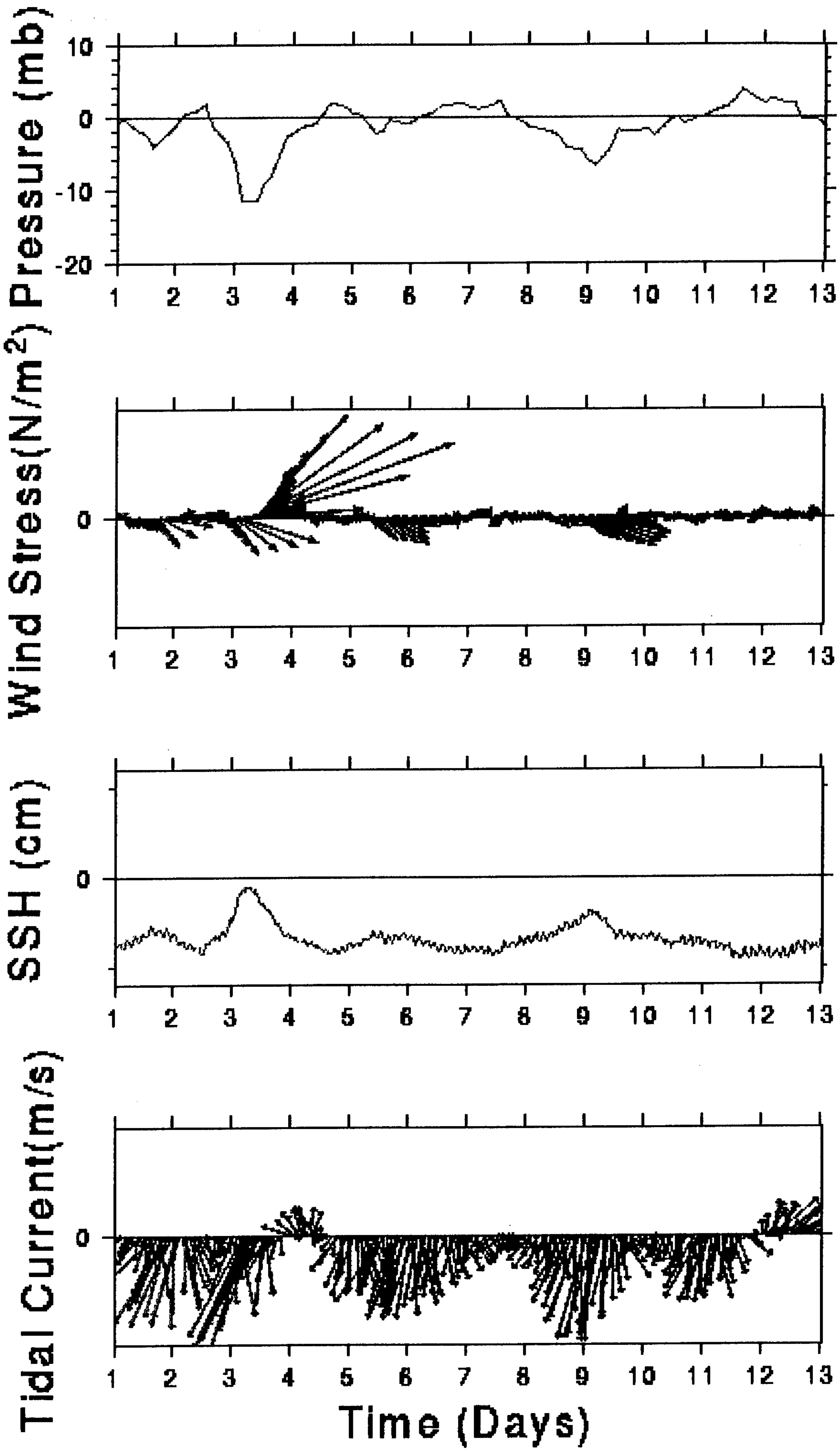


Wind Stress



Pressure(mb)

Figure A8.



Pressure (mb)
10
0
-10
-20
Wind Stress(N/m2)
0
SSH (cm)
0
Tidal Current(m/s)
0
1 2 3 4 5 6 7 8 9 10 11 12 13
Time (Days)

Figure A9.

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Kantha,L.H., C. Tierney, J.W. Lopez, S.D. Desai, M.E. Parke, and L. Drexler, 1995. Barotropic tides in the global oceans from a nonlinear tidal model assimilating altimetric tides: 2. Altimetric and Geophysical Implications,*J. Geophys. Res.*, 100, 25,309-25,317.

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Westerink, J.J., C.A. Blain, R.A. Luettich, Jr., N.W. Scheffner, 1994. ADCIRC: An advanced three-dimensional cirrculation model for shelves, coasts, and estuaries; Report 2: User's manual for ADCIRC-2DDI. *Dredging Research Program Technical report DRP-92-6*, Coastal Engineering Research Center, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS 39180.

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13. Abstract *(Maximum 200 words).*

This report documents an existing capability to produce operationally relevant products on sea level and currents from a tides/storm surge model for any coastal region around the world within 48 hours from the time of the request. The model is ready for transition to the Naval Oceanographic Office (NAVOCEANO) for potential contingency use anywhere around the world. A recent application to naval operations offshore Liberia illustrates this. Mississippi State University, in collaboration with the University of Colorado and NAVOCEANO, successfully deployed the CURReNTSS (Colorado University Rapidly Relocatable Nestable Tides and Storm Surge) model that predicts sea surface height, tidal currents and storm surge, and provided operational products on tidal sea level and currents in the littoral region off south-western coast of Africa. This report summarizes the results of this collaborative effort in an actual contingency use of the relocatable model, summarizes the lessons learned, and provides recommendations for further evaluation and transition of this modeling capability to operational use.

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(U) Liberia (U) Navy (U) Coastal

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